AEROSPACE
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CONTINUED INVESTIGATION OF SOLID PROPULSION ECONOMICS

Task 4
Cost Projections for New Sounding Rockets and Upper Stages

Prepared for:

NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
WASHINGTON, D.C.

September 1967

STANFORD
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INSTITUTE

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ABSTRACT

An economic analysis has been made of advanced, high energy solid, hybrid, and RSVP (restartable solid variable pulse) propulsion systems applied to upper stages for medium launch vehicles, particularly the Atlas Agena, and to high altitude sounding rockets. The study investigates the present state of the art represented by these three propulsion concepts, estimates probable expenditures required prior to initiation of formal development programs, estimates the development programs themselves, projects procurement and launch costs for vehicles using the new propulsion systems, determines cost-effectiveness estimates for the new vehicles, and compares these with cost-effectiveness estimates for current launch vehicles and sounding rockets.

Results of the study of upper stage applications indicate that a relatively small investment is required to bring the technology of advanced solid hybrid and RSVP propulsion to a state applicable to full scale development in motors of Agena and Agena kick stage size. When either propellant concept is used, more cost-effective vehicles result compared with the SLV3X Agena. Using hybrid propulsion for a kick stage, the SLV3X Agena becomes more cost-effective than the SLV3X Centaur in both high velocity and high altitude circular earth orbit missions, including synchronous missions.

Application of the new propulsion concepts to sounding rockets indicates a general increase in cost-effectiveness when compared with current vehicles. Further research is required to determine the specific applications that are most appropriate for the new systems.

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INTRODUCTION

This report describes an economic analysis of advanced, high energy solid, hybrid, and restartable solid propulsion systems as applied to upper stages for medium launch vehicles used by the National Aeronautics and Space Administration. The report also describes a preliminary economic analysis of hybrid and advanced solid propulsion applied to sounding rockets.

In the upper stage applications, three types of advanced propulsion systems are primarily considered: (1) beryllium-augmented solids; (2) cryogenic (FLOX/Li/LiH) hybrids; and (3) liquid-augmented restartable solids (restartable solid variable pulse or RSVP). A beryllium wafer solid restartable motor is also considered in this part of the study, but in less detail than the other propulsion concepts.

In the sounding rocket applications, hybrid motors using a propellant combination of H_2O_2 and polyethylene and solid motors using aluminum-augmented grains are considered.

Background of the Study

In 1965, it was apparent to NASA that the technology of high energy hybrid, advanced single impulse solid and restartable solid propulsion systems had reached a point at which specific applications might be investigated. These propulsion systems exhibited apparent advantages in certain applications, such as less complexity, less severe handling requirements, and lower cost compared with conventional liquids, higher performance and greater flexibility compared with conventional solids, and space storability and sterilization using certain propellants.

To investigate these advantages, particularly performance, three prime contractors, Douglas Aircraft Company, Lockheed Missiles and Space Company, and Space General Corporation were selected by NASA to pursue systems and preliminary design studies applying each of these types of propulsion to upper stages (Douglas and Lockheed) and to sounding rockets (Space General). The results of these studies indicated that the application of the new propulsion systems considerably increased the usefulness and capability of the respective vehicles. For example, Douglas showed (Ref. 1) that a new hybrid third stage, when applied to the Thrust Augmented Thor Improved Delta (TAT Delta), increased its payload carrying capability to 1,125 pounds for a 2,000-nautical mile circular orbit compared with 125 pounds for the Delta alone. Similarly, Lockheed determined (Ref. 2) that the payload capability of the uprated Atlas Agena (SLV3X Agena) could be increased to 1,747 pounds compared with 580 pounds for the SLV3X Agena alone, in a 24-hour synchronous orbit, using a hybrid third stage.

The performance increase provided by the new propulsion systems in sounding rocket applications was not identified by Space General in a way that allowed specific comparisons of cost and performance on an item by item basis. However, families of new hybrid and advanced solid sounding rockets were conceptually designed and performance values were obtained that indicated in a general way an improvement over current vehicles. All of these results indicated that comparative cost analyses should be performed to determine trade-offs of cost and performance taken together.

The present study is such an analysis. Each of the new propulsion concepts--hybrid, solid, and RSVP--is examined as applied to the uprated Atlas Agena (SLV3X Agena). Comparative information is also presented concerning certain wafer-solid motors designed by Douglas for the TAT Delta and Scout upper stages, and similar analyses are performed for sounding rockets. The study of upper stage applications considers (1) the probable cost of developing new motors and stages, using each propulsion concept; (2) the cost of further improvements in technology required to bring the state of the art to a point at which full scale development programs may be initiated; (3) the probable first unit production cost of fully developed motors, stages, and launch vehicles; (4) the extrapolation of the latter costs to likely procurement, according to present plans for NASA missions; and (5) the cost-effectiveness of the new launch vehicles compared with the SLV3X Agena and the SLV3X Centaur.*

For sounding rockets, the study considers (1) the cost and performance of representative current vehicles; (2) the estimated cost and performance of new vehicle families, using hybrid and advanced solid propulsion; and (3) the estimated cost-effectiveness of both new and old vehicles.

Scope

Upper Stages

The scope of the study is defined by the series of launch vehicles and upper stages designed by Lockheed in References 2 and 3. These vehicles--with new upper stages identified--are summarized in Table 1 and illustrated in Figures 1 through 8.

Briefly, each of the vehicles uses an advanced version of the Atlas Agena (SLV3X Agena) as a first stage; either the standard Agena or a new hybrid as a second stage; and in some cases, third stages using each of the new types of propulsion, hybrid, advanced solid, and RSVP.

---

* Wafer-solid motors are not carried through the study to stage and launch vehicle analysis because this effort was performed by Douglas in its previous systems study (Ref. 1).

Table 1

LAUNCH VEHICLE SUMMARY

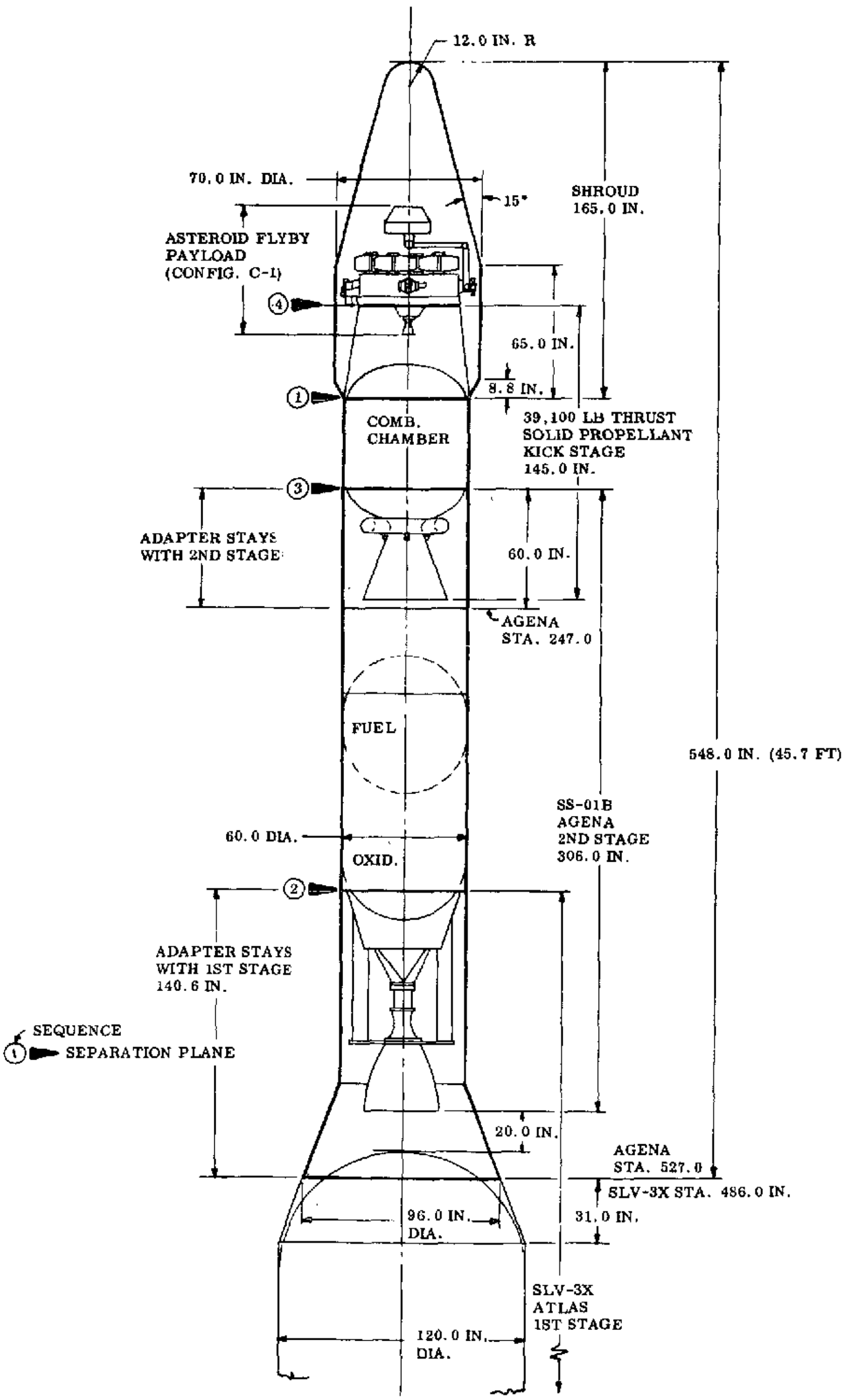
	LV-1	LV-2	LV-9	LV-3	LV-4	LV-5	LV-6	LV-7	LV-8	LV-10
Mission	← Asteroid Mission →			← 24-Hour Synchronous Orbit →						
First Stage	SLV3X	SLV3X	SLV3X	SLV3X	SLV3X	SLV3X	SLV3X	SLV3X	SLV3X	SLV3X
Second Stage	Agena	Agena	Agena	Agena	Agena	Hybrid	Hybrid	Hybrid	Agena	Agena
Thrust (lb)	16,000	16,000	16,000	16,000	16,000	20,000	20,000	20,000	16,000	16,000
Prop. Wt. (lb)	13,350	13,350	13,350	13,350	13,350	14,000	14,000	14,000	13,350	13,350
Stage Number						1	1	1		
Third Stage	Solid	Hybrid	RSVP	--	Hybrid	--	Solid	Hybrid	Solid	RSVP
Thrust (lb)	39,100	10,000	15,000		10,000		8,500	10,000	8,500	15,000
Prop. Wt. (lb)	5,000	5,000	5,500		5,000		1,000	5,000	1,000	5,500
Stage Number	3	2	5		2		4	2	4	5

New stages are enclosed by dashed lines and stage numbers indicated in text.

Source: Lockheed Missiles and Space Company.

FIGURE 1

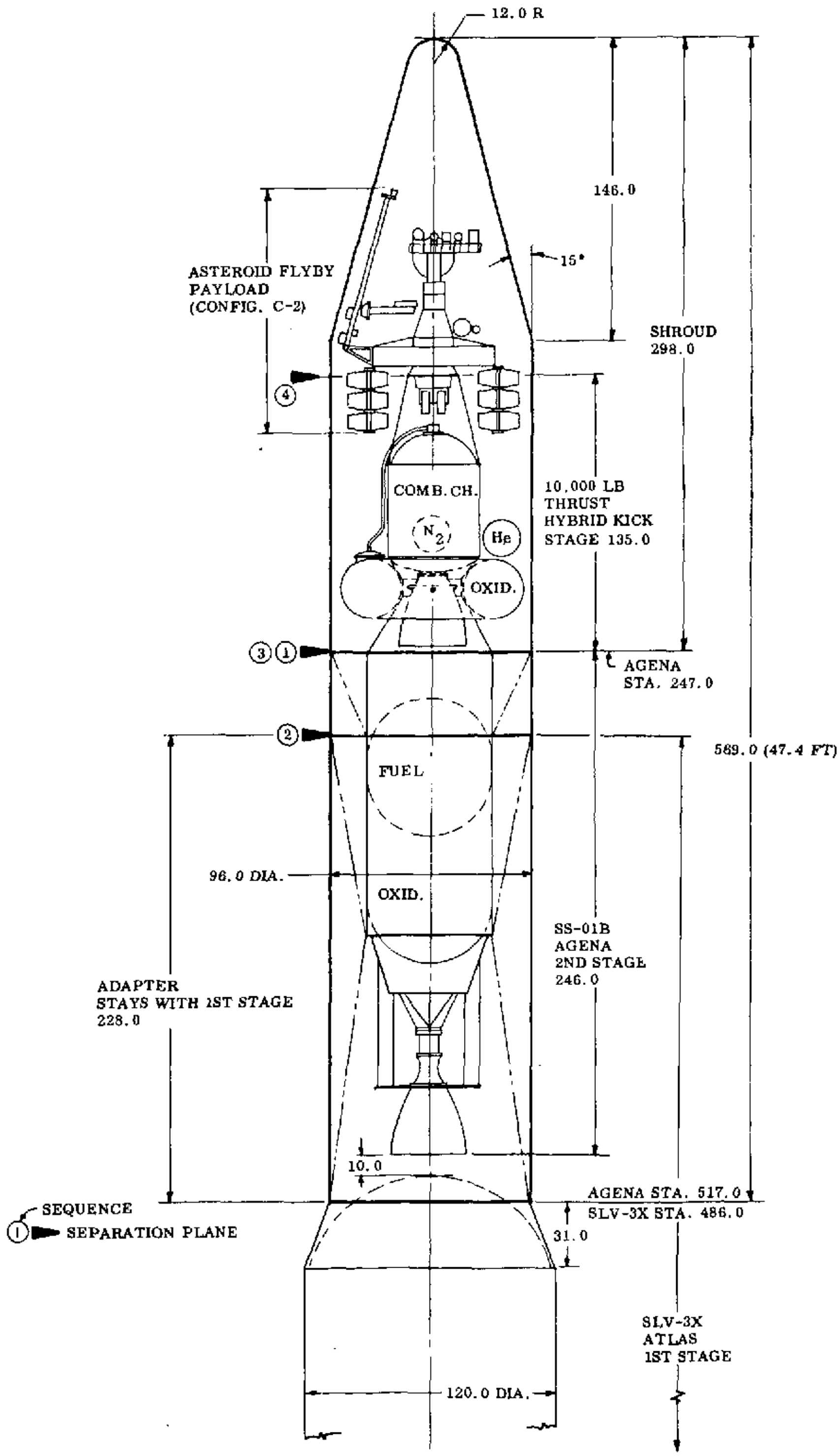
LAUNCH VEHICLE LV-1



SOURCE: Lockheed Missiles & Space Company.

FIGURE 2

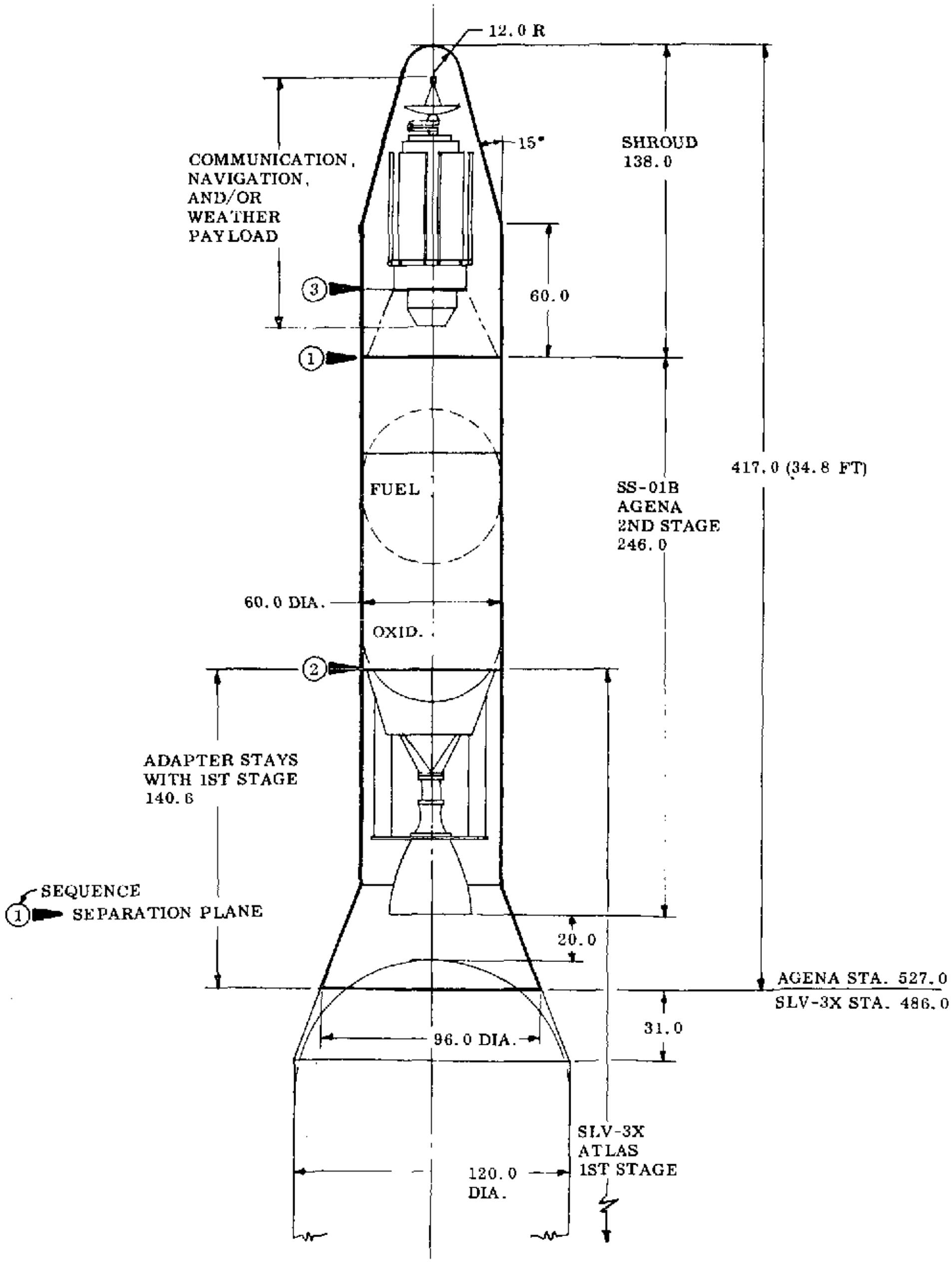
LAUNCH VEHICLES LV-2 AND LV-4



SOURCE: Lockheed Missiles & Space Company.

FIGURE 3

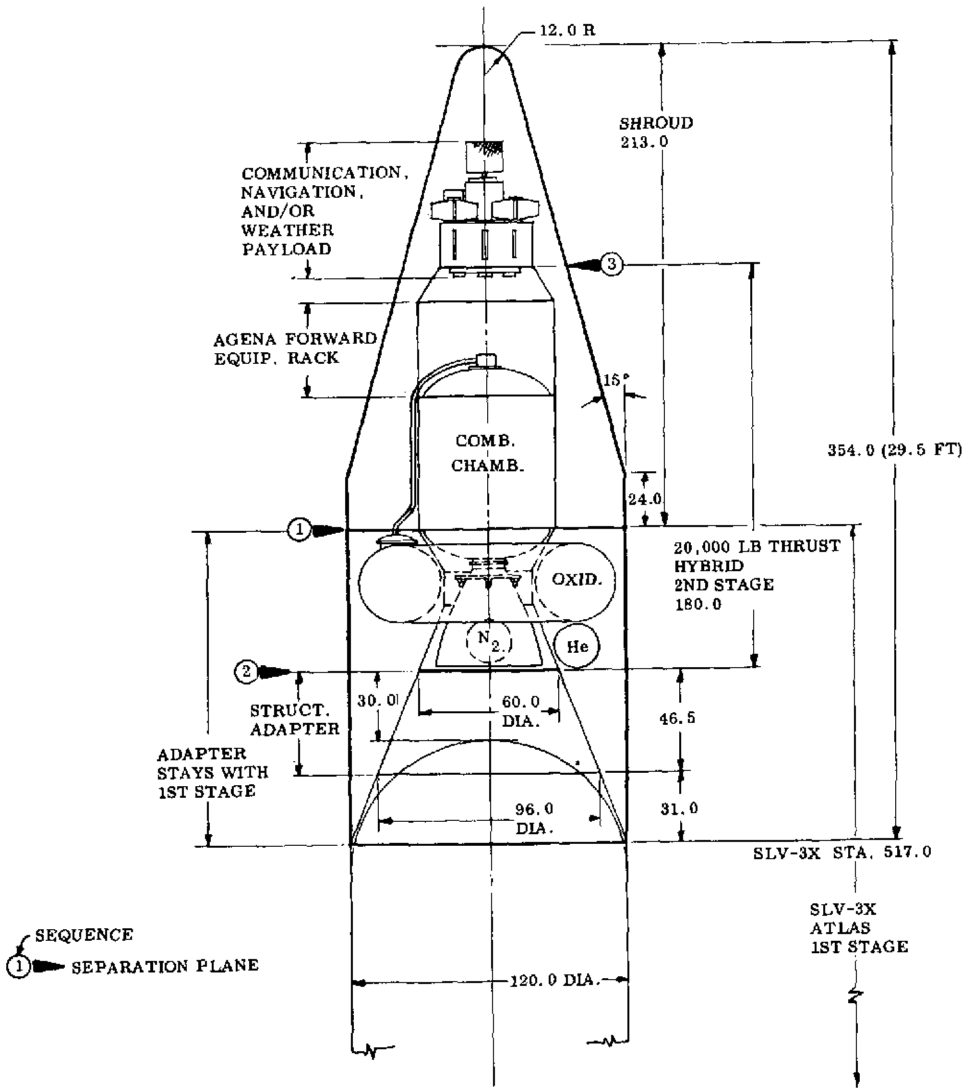
LAUNCH VEHICLE LV-3



SOURCE: Lockheed Missiles & Space Company.

FIGURE 4

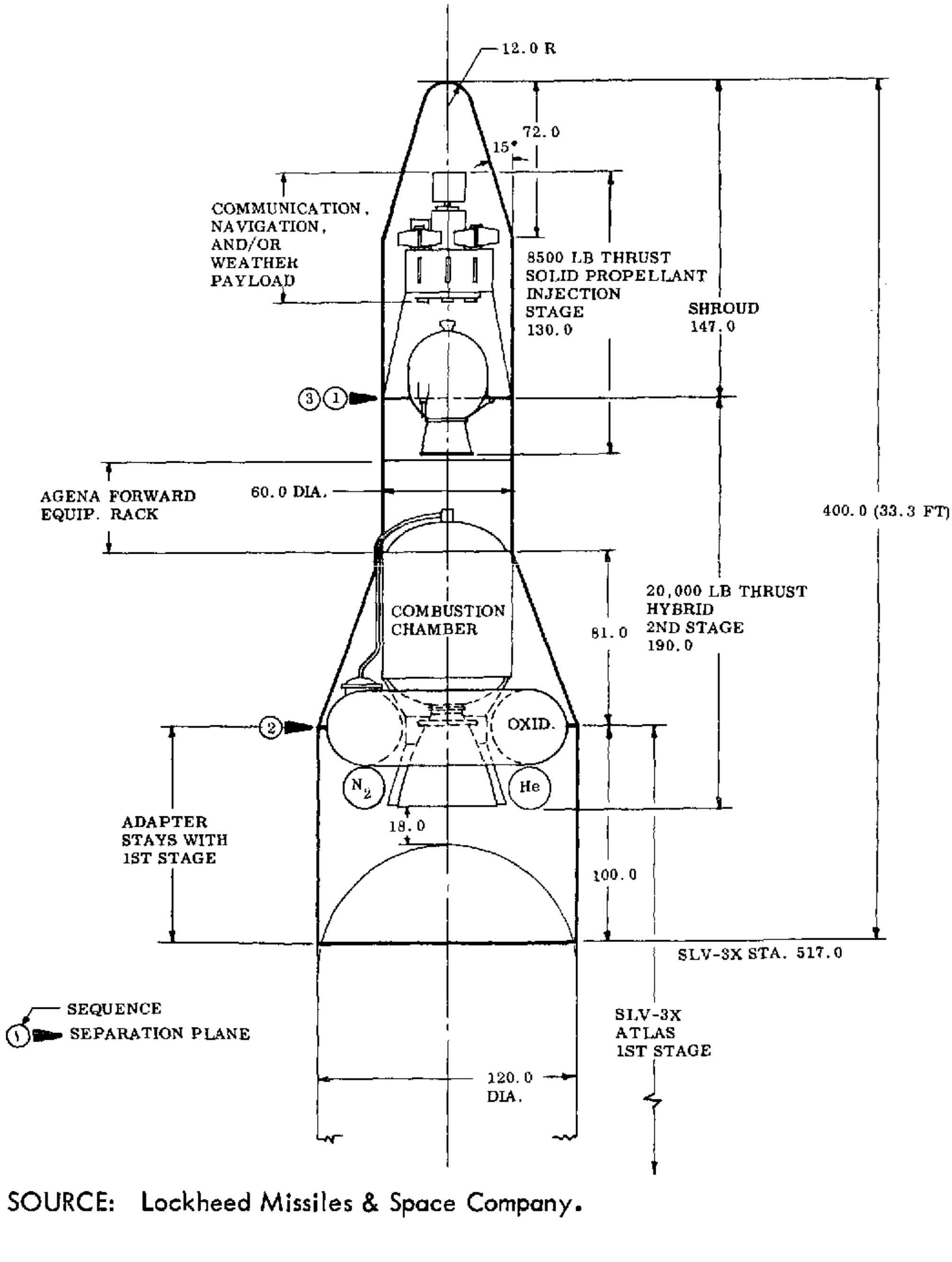
LAUNCH VEHICLE LV-5



SOURCE: Lockheed Missiles & Space Company.

FIGURE 5

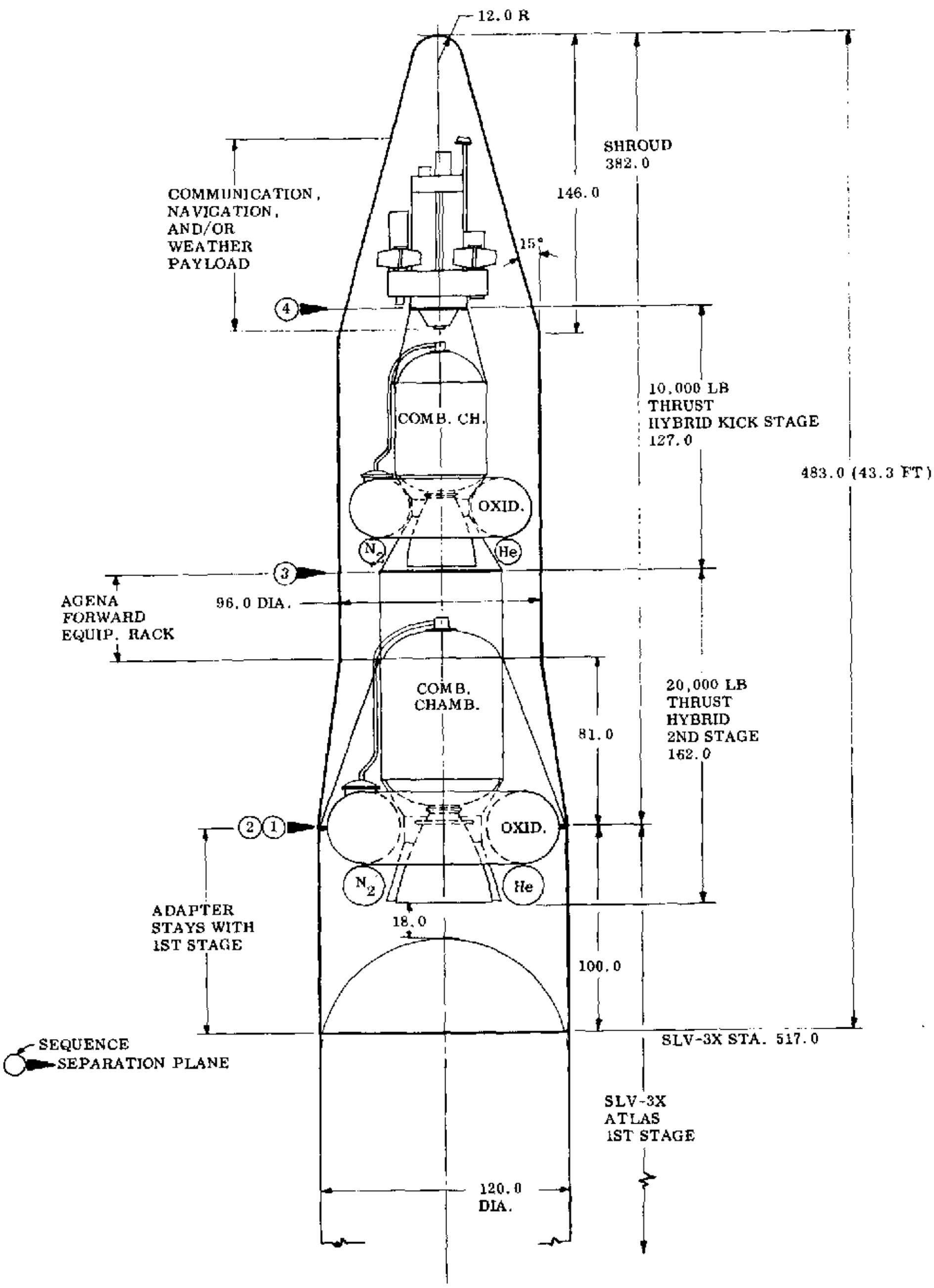
LAUNCH VEHICLE LV-6



SOURCE: Lockheed Missiles & Space Company.

FIGURE 6

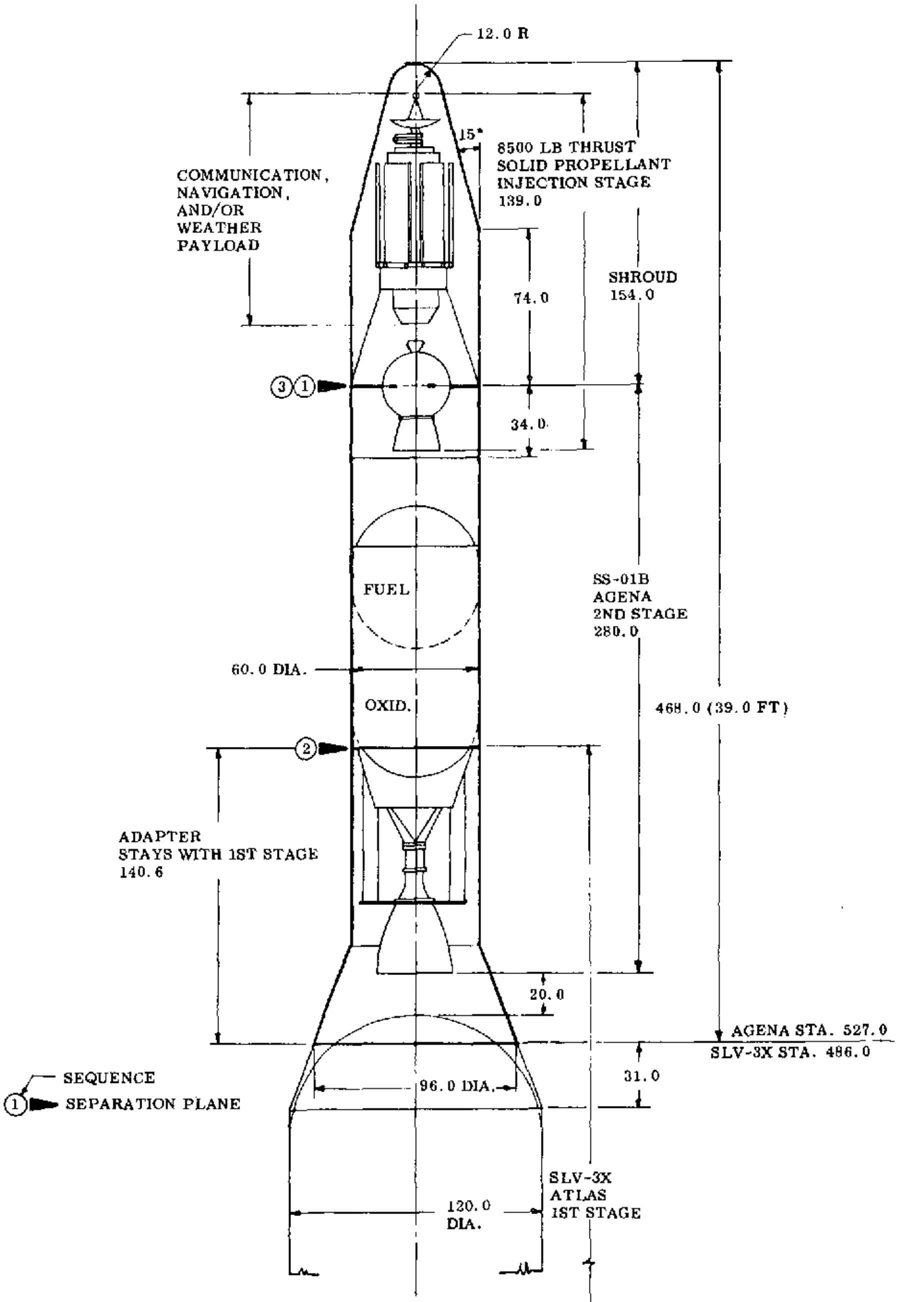
LAUNCH VEHICLE LV-7



SOURCE: Lockheed Missiles & Space Company.

FIGURE 7

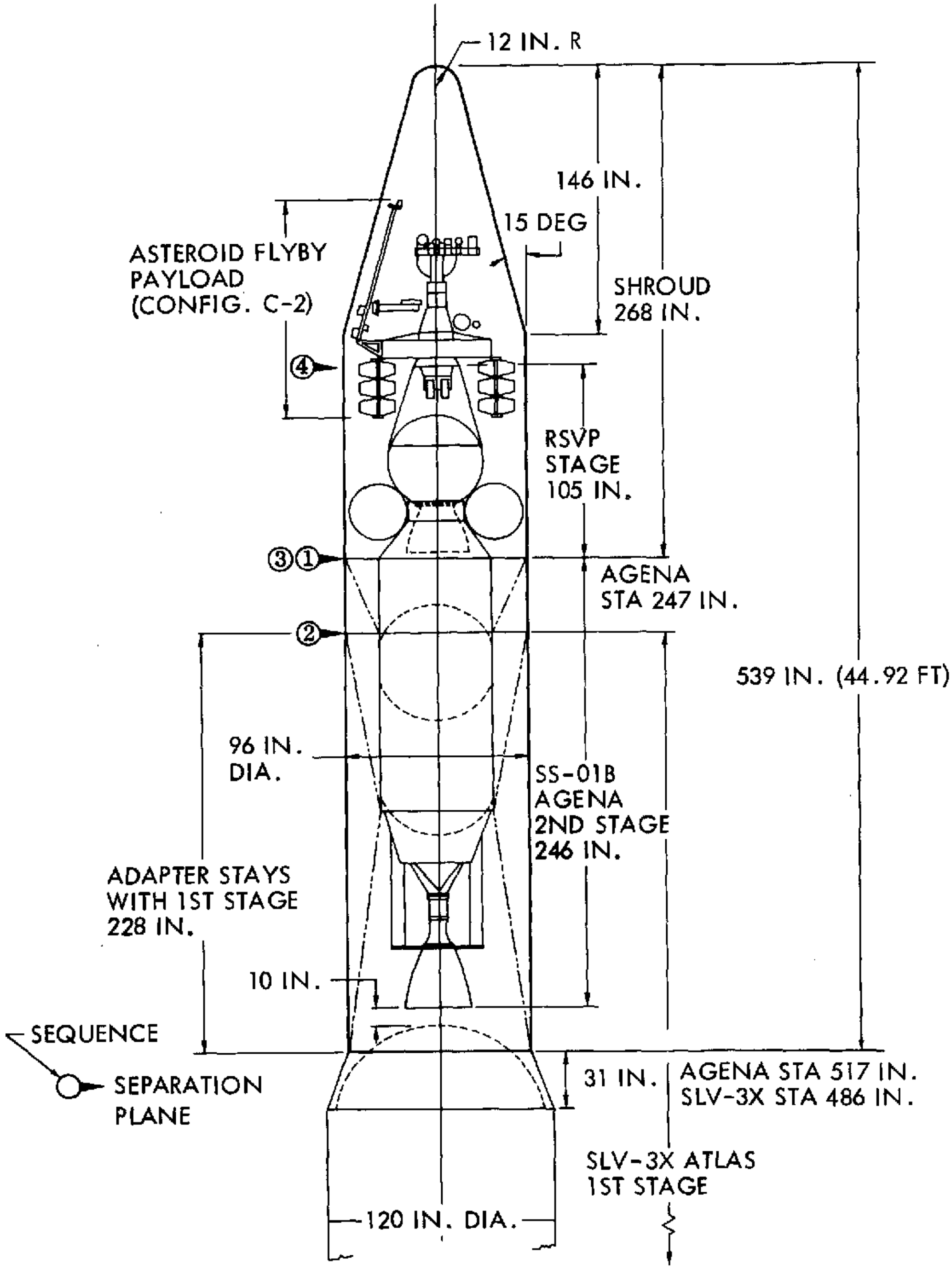
LAUNCH VEHICLE LV-8



SOURCE: Lockheed Missiles & Space Company.

FIGURE 8

LAUNCH VEHICLES LV-9 AND LV-10



SOURCE: Lockheed Missiles & Space Company.

To size the upper stages for the vehicles, Lockheed considered two specific missions (1) a high velocity Asteroid belt fly-through mission, and (2) a 24-hour synchronous earth orbit mission. A variety of optimum motor sizes resulted for both second and third stage applications for each mission and five basic stages evolved, as follows:

Stage Number	Description
1	20,000-pound thrust hybrid second stage replacing Agena (14,000 pounds propellant)
2	10,000-pound thrust hybrid kick stage above Agena (5,000 pounds propellant)
3	39,100-pound thrust advanced solid kick stage above Agena (5,000 pounds propellant)
4	8,500-pound thrust advanced solid injection stage above Agena (1,000 pounds propellant)
5	15,000-pound thrust RSVP restartable solid third stage above Agena (5,500 pounds propellant)

The above stages were applied to the SLV3X launch vehicle to achieve the configurations shown in Table 1. Launch vehicles LV-1, LV-2, and LV-9 were established to evaluate the three new propulsion types, as third stages over Agena, in the Asteroid mission; launch vehicles LV-3 and LV-5 were established to compare the standard Agena with the new 20,000-pound thrust hybrid second stage; launch vehicles LV-4, LV-8, and LV-10 were used to evaluate the three new propulsion types as third stages in the synchronous orbit mission; and launch vehicles LV-6 and LV-7 were used to compare solid and hybrid third stages over the hybrid second stage.

As indicated above, costs were developed in this study for each of these vehicles, by considering the motors, stages, and other components. These costs were then combined with the performance values determined by Lockheed to establish cost-effectiveness for each vehicle.

Sounding Rockets

The scope of the study of sounding rocket applications was basically defined by the families of hybrid and advanced solid building-block designs for these vehicles, which were developed by Space General Corporation. These families are described in detail in Part II of this report. Briefly, however, the hybrids are of two types--constant thrust and blowdown (decreasing thrust)--and three sizes--60,000 lb-sec, 250,000 lb-sec, and 800,000 lb-sec total thrust. The advanced solid family is also composed of two types--end burners and radial burners--and covers a range of total impulses from 0.3 million to 2.4 million lb-sec.

Method of Approach

Upper Stages

Initial steps in the upper stage study consisted of (1) determining briefly the present state of the art for each propulsion concept; (2) identifying state-of-the-art improvements needed before initiation of full scale development efforts; and (3) estimating the probable minimum cost of such improvements.

After the above steps were completed, cost estimates for development of the required propulsion systems were collected from the following manufacturers:

1. Aerojet General Corporation
2. Atlantic Research Corporation
3. Hercules, Incorporated
4. Lockheed Propulsion Company
5. Thiokol Chemical Co.
6. United Technology Center

The data obtained were categorized by format, compared and analyzed for similarities and differences, and plotted to isolate trends. From this analysis, estimated costs for the several solid motors and hybrid and RSVP thrust chamber assemblies were developed. These costs were compared with independently derived SRI estimates that were assembled from costs for individual components or ingredients and from SRI specifications of requirements for fabricating and testing such units.

From the above, cost estimating relationships were derived expressing development, test, and evaluation costs for these motor components as a function of propellant weight. First unit production costs were also established as a function of propellant weight, and 95% and 90% learning curves were chosen to enable the computation of procurement costs for the specific motors required.

Under subcontract to SRI, Lockheed furnished cost estimates for stage development and integration and for oxidizer storage and delivery system development and production in the case of the hybrid motors (Ref. 4). Combining these estimates with those for the motors and thrust chambers developed previously, computations were made of the total development cost for each of the five stages evaluated. Costs of launch vehicle booster test hardware and launch services were added for each vehicle concept to derive total RDT&E costs for each of the 10 configurations evaluated in the study.

To determine the cost-effectiveness of the 10 vehicles, SRI assumed two launch programs, at rates of 6 launches and 12 launches per year, over a 10-year period. Conservative estimates were made to take into account cost reductions experienced as a result of learning--95% at the 6 per year rate and 90% at the 12 per year rate--and the total cost of operations was established for each launch program. These costs were combined with vehicle performance to determine operational cost-effectivness--that is, operations cost per pound of delivered payload in each of the missions considered. Nonrecurring RDT&E costs were added to operations costs to determine total cost-effectiveness for each vehicle concept.

Sounding Rockets

A different approach was used in determining the cost and cost-effectiveness of sounding rockets, because specific vehicles could not be compared, as in the upper stage study. A more general approach was required, which relied more heavily on statistical techniques.

The first step in the study was to determine a measure of cost-effectiveness for sounding rockets that would be similar to dollars per pound of delivered payload used in evaluating the cost-effectiveness of larger vehicles and upper stages. Using this measure--dollars per pound-mile--cost-effectiveness was calculated for current sounding rockets. Performance criteria were developed for the hybrid and advanced solid sounding rockets designed by Space General, and cost data were developed for the new concepts by extrapolating known costs for current vehicles. Performance and cost data were then combined to estimate the cost-effectiveness of new sounding rockets.

SUMMARY

Upper Stages

Technology Improvement

It is estimated that approximately $1.5 million to $2 million will be required to bring the technology of cryogenic hybrids (FLOX/Li/LiH) to the point of formal development. The primary requirements still to be met are:

1. Development of high temperature, corrosion resistant nozzle throat materials

2. Design of efficient nozzle expansion cone contours to relieve problems of nonequilibrium flow

3. More satisfactory grain utilization

For the beryllium-augmented solids investigated in this study (Be/HMX), it is estimated that a minimum expenditure of $0.5 million will be required for technology improvements. The remaining problems are concerned primarily with propellant characterization.

Although RSVP technology is at an early stage, only minor problems are apparent when propellants and oxidizers called for in current studies are used. It is estimated that $0.5 million will be required for further research and technology efforts on this propulsion concept before formal development can be initiated.

Motor Development

RDT&E costs for hybrid thrust chamber assemblies range from $3.9 million for motors with a propellant weight of 2,000 pounds to $6.8 million for motors with a propellant weight of 14,000 pounds. Development costs for hybrid oxidizer storage and delivery systems were estimated on the basis of 5,000 and 14,000 pounds and are $10.7 million and $15.7 million, respectively.

Development costs for advanced solid, beryllium-augmented motors are estimated to range from $4.3 million for motors with a propellant weight of 1,000 pounds to $8.6 million for motors with a propellant weight of 7,000 pounds.

Two sizes of wafer-solid motors were considered--650 pounds and 2,000 pounds. Development of these motors is estimated to require $6.5 million and $14 million, respectively.

An RSVP motor with a propellant weight of 5,500 pounds is estimated to require $6.3 million for development of the solid motor and $8.1 million for development of the fluid control system, or total development costs of $14.4 million.

Stage and Vehicle Development

RDT&E costs for each of the five stages evaluated during the study are shown in the following tabulation:

Stage	RDT&E Costs (millions of dollars)
Hybrid second stage	$76.5
Hybrid kick stage	74.0
Solid kick stage	60.7
Solid injection stage	58.0
RSVP kick stage	69.8

RDT&E costs for the 10 vehicles evaluated vary from $58 million for the LV-8 vehicle (SLV3X/Agena/solid) to $113 million for the LV-7 vehicle (SLV3X/hybrid/hybrid). Costs per launch are similar for all 10 vehicles: first unit costs range from $7.2 million for LV-5 (SLV3X/hybrid) to $9.6 million for LV-4 (SLV3X/Agena/hybrid); cumulative average costs for 60 launches are $6.2 million and $8.4 million, respectively.

Cost-Effectiveness of Launch Vehicles

Tables 2 and 3 summarize the operational and total cost-effectiveness of the 10 vehicles evaluated and the SLV3X Centaur in each mission, Asteroid flythrough and synchronous orbit.* Table 3 gives the estimates derived for a program of 60 launches, and Table 4 presents these figures for a program of 120 launches. The results of the evaluations indicate that:

1. All vehicles evaluated are more cost-effective than the SLV3X Agena.

---

* The following figures were used in determining cost-effectiveness of the SLV3X Centaur: cost, $14.9 million per launch (Ref. 5); performance, 2,000 pounds at 39,600 ft/sec (synchronous orbit mission) and 700 pounds at 42,800 ft/sec (Asteroid mission) (Ref. 6) p. 10 footnote.

Table 2

COST AND COST-EFFECTIVENESS SUMMARY FOR
A LAUNCH PROGRAM OF 60 VEHICLES

Launch Vehicle Designation	Launch Vehicle Description	Payload per Launch (lb)	Total Delivered Payload (lb x 10^{-3})	RDT&E Cost (millions of $)	Operations Cost (millions of $)	Operational Cost-Effectiveness ($/lb-payload)	Total Cost-Effectiveness ($/lb-payload)
			Asteroid Mission				
LV-2	SLV3X/Agena/hybrid	1,140	68.4	$ 74.0	$481.2	$7,035	$ 8,116
LV-1	SLV3X/Agena/solid	823	49.4	60.7	458.3	9,277	10,506
LV-9	SLV3X/Agena/RSVP	825	49.5	69.8	480.2	9,701	11,111
	SLV3X/Centaur*	700	42.0	0	750.0	17,857	17,857
			Synchronous Orbit Mission				
LV-3	SLV3X/Agena*	580	34.8		428.4	12,310	12,310
LV-4	SLV3X/Agena/hybrid	1,747	104.8	75.9	532.2	4,792	5,516
LV-8	SLV3X/Agena/solid	1,054	63.2	58.0	467.5	7,397	8,315
LV-10	SLV3X/Agena/RSVP	1,360	81.6	71.7	501.2	6,142	7,021
LV-5	SLV3X/hybrid	1,410	84.6	76.2	374.1	4,422	5,323
LV-7	SLV3X/hybrid/hybrid	2,320	139.2	113.0	447.3	3,213	4,025
LV-6	SLV3X/hybrid/solid	1,783	107.0	95.1	413.2	3,862	4,750
	SLV3X/Centaur*	2,000	120.0	0	750.0	6,250	6,250

* Reference vehicles.

Source: Stanford Research Institute.

Table 3

COST AND COST-EFFECTIVENESS SUMMARY FOR
A LAUNCH PROGRAM OF 120 VEHICLES

Launch Vehicle: Designation	Launch Vehicle: Description	Payload per Launch (lb)	Total Delivered Payload (lb x 10^{-3})	RDT&E Cost (millions of $)	Operations Cost (millions of $)	Operational Cost-Effectiveness ($/lb-payload)	Total Cost-Effectiveness ($/lb-payload)
			Asteroid Mission				
LV-2	SLV3X/Agena/hybrid	1,140	136.8	$ 74.0	$ 799.5	$ 5,844	$ 6,385
LV-1	SLV3X/Agena/solid	823	98.8	60.7	756.5	7,657	8,271
LV-9	SLV3X/Agena/RSVP	825	99.0	69.8	798.1	8,062	8,767
	SLV3X/Centaur*	700	84.0	0	1,168.0	13,904	13,904
			Synchronous Orbit Mission				
LV-3	SLV3X/Agena*	580	69.6	0	714.0	10,258	10,258
LV-4	SLV3X/Agena/hybrid	1,747	209.6	75.9	839.2	4,004	4,366
LV-8	SLV3X/Agena/solid	1,054	126.5	58.0	779.4	6,161	6,620
LV-10	SLV3X/Agena/RSVP	1,360	163.2	71.7	837.7	5,133	5,572
LV-5	SLV3X/hybrid	1,410	169.2	76.2	608.8	3,598	4,048
LV-7	SLV3X/hybrid/hybrid	2,320	278.4	113.0	731.5	2,628	3,033
LV-6	SLV3X/hybrid/solid	1,783	214.0	95.1	671.8	3,139	3,584
	SLV3X/Centaur*	2,000	240.0	0	1,168.0	4,867	4,867

* Reference Vehicles.

Source: Stanford Research Institute.

2. Hybrid vehicles are especially attractive, since they are more cost-effective than even the highly rated SLV3X Centaur for both types of missions and at both usage rates.

Table 3 shows that the SLV3X/hybrid/hybrid combination is the most cost-effective of all vehicles evaluated despite its development cost of $113 million. Total cost per pound of delivered payload for this vehicle in the synchronous orbit mission is about $4,000. Corresponding figures for the SLV3X Agena and SLV3X Centaur are $12,300 and $6,250. Other vehicles evaluated for the synchronous orbit mission include the SLV3X/hybrid/solid, which has a cost-effectiveness of $4,750 per pound of delivered payload, and the SLV3X/Agena/hybrid, which has a cost-effectiveness of $5,500 per pounds of delivered payload.

Sounding Rockets

A general increase in cost-effectiveness may be expected to occur from the use of hybrid and advanced solid propulsion in sounding rockets. Using generalized designs for the estimation of such increases, it appears that cost-effectiveness could improve from an average of $1 to $2 per pound-mile for current vehicles and 50¢ to $1 for new vehicles. These projections assume (1) that performance of the new vehicles will be substantially above the average for current vehicles and (2) that costs for the new vehicles will be about the same as average costs for current vehicles.

CONCLUSIONS AND RECOMMENDATIONS

The major conclusions reached as a result of this study are:

1. Each of the three types of advanced propulsion investigated--hybrid, advanced solid, and RSVP--has the capability for significantly increasing the cost-effectiveness of the uprated SLV3X Agena when used as a third stage on that vehicle.

2. A vehicle having the SLV3X as a first stage and a new hybrid second stage is significantly more cost-effective than the SLV3X Agena, especially at velocities near the limits of Agena capability (approximately 40,000 ft/sec).

3. Development, qualification, and flight testing of vehicles using hybrid, advanced solid, or RSVP propulsion would cost between $58 million for a third stage solid vehicle and $110 million for a vehicle having new hybrid motors in both second and third stages.

4. This development cost would be amortized with the launching of less than 10 new vehicles in all cases and with the launching of less than five vehicles in the case of hybrid second stage plus hybrid third stage vehicles.

5. State-of-the-art improvements required to initiate the above development programs are relatively minor. Advancements required for hybrids are estimated to cost between $1.5 million and $2 million; advancements required for beryllium-augmented and RSVP motors are estimated at $0.5 million.

6. Cost-effectiveness of sounding rockets could be substantially improved by using hybrid or advanced solid propulsion. Cost-effectiveness values of 50¢ per pound-mile of delivered payload appear to be achievable, compared with $1 to $2 per pound-mile for conventional sounding rockets.

The following recommendations are made for further study:

1. Examine a compromise third stage hybrid or advanced solid, usable on both Atlas Agena and Thor Delta. (Recently designed Douglas third stages having 4,000 pounds of propellant may be applicable.)

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2. Examine OSSA mission projections in detail to identify more precisely those missions in which hybrid or advanced solid vehicles may be effectively used.

3. Continue advancement of hybrid technology by supporting development of high temperature-resistant materials.

4. Continue advancement of RSVP technology by supporting research on high pressure exponent propellants.

5. Initiate further research to establish conclusive sounding rocket vehicle designs that may be analyzed in detail for cost and cost-effectiveness implications.

Part I

UPPER STAGE APPLICATIONS

TECHNOLOGY IMPROVEMENT

Before performing the cost estimates for the 10 vehicles, SRI conducted a preliminary survey of the state of technological development in the fields of propulsion of interest in the study. This survey was conducted to gain an overview of the state of the art as a base for estimating the cost of further research required prior to the initiation of formal, mission-oriented development programs. Specifically, an estimate was sought of the minimum cost to translate the present technology of hybrid, advanced solid and RSVP propulsion to a level acceptable for formal development programs, using conceptual designs and propellant combinations identified in the previous Lockheed systems studies (Refs. 2 and 3).

The survey assumptions were:

- For hybrid propulsion
  - Lockheed designs for 10,000- and 20,000-pound thrust motors
  - FLOX/Li/LiH propellant
- For advanced solid propulsion
  - Lockheed designs for 39,100- and 8,500-pound thrust motors
  - Beryllium-augmented, double-base propellant using HMX oxidizer*
- For RSVP propulsion
  - Lockheed design for 15,000-pound thrust motor
  - Aluminum-augmented, double-base propellant with liquid fluorine control fluid

The present section identifies problems remaining in translating the present technology to that required for development of the above motors and estimates costs for solving those problems. A summary of the results is presented in Table 4 and each technology area is discussed in the sections which follow.

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* HMX oxidizer (cyclotetramethylenetetranitramine) was substituted for TAZ oxidizer (triaminoguanidine azide) in the study because initial investigations showed substantial problems with the latter oxidizer in addition to those discussed by Lockheed in Reference 2. Because of these problems, the use of TAZ is now considered to be very unlikely in the time period under consideration.

Table 4

TECHNOLOGY IMPROVEMENT REQUIREMENTS FOR SPECIFIC
MOTORS AND PROPELLANT COMBINATIONS

Propulsion Concept	Motor Thrust (lbs)	Propellants	Problem Area	Minimum Cost for Solution (millions of $)
Hybrid	10,000-20,000	FLOX/Li/LiH	Nozzle throat materials	$0.6 - 1.0
			Nozzle design to reduce kinetic losses	0.4 - 0.6
			Fuel utilization	0.2
Advanced solid	8,500-39,100	Be/HMX	Propellant characterization	0.5
Liquid-augmented solid (RSVP)	15,000	F_2/Al/HMX	High pressure exponent propellant Combustion efficiency	0.5

Source: Stanford Research Institute.

Hybrid Motors

The most critical R&D area for hybrid motors is the improvement of materials for the throat section of the nozzle. On-going research efforts at TRW and elsewhere* have established that certain composite materials, such as pyrolized tantalum carbide, can withstand the environment of a FLOX/Li/LiH hybrid motor under conditions of 200-psi chamber pressure and 6000°F flame temperature for a total burning time of 70 seconds (Ref. 7). However, these conditions are only partially those expected in a fully operational upper stage. Therefore, it is estimated that approximately $0.6 million to $1 million will be required to develop materials that are acceptable for the full scale application. This estimate is based on the following assumptions and mission requirements (Refs. 1, 2, and 8):

1. Chamber pressures required for efficient operation of either second or third stage hybrid engines are about 250-300 psi.

2. Operating temperatures exceed 7000°F.

3. Duty cycle requires up to 10 restarts in space, total burning times of 120 seconds, continuous burning times of 70 seconds, and cool-down times of several seconds to several hours.

The second most important area requiring additional research and development is the design of the nozzle (Ref. 9). The particular problem here concerns kinetic losses in the nozzle resulting from nonequilibrium flow. Attempts to overcome this problem are hampered by the fact that no vacuum testing of hybrids has as yet taken place. Based on assumptions that lightweight, highly efficient nozzles will be required for any of the upper stages specified, an estimate of $0.4 million to $0.6 million is made for this portion of technology improvement.

The third problem area of hybrid motors is fuel utilization (Ref. 10). This problem is not as serious as those mentioned above, since unburned fuel merely lowers the efficiency of the motor rather than making it inoperable, and these contingencies have been taken into account in the systems studies. Higher mass ratios and total impulses will be required in hybrids, however, much as they have been in solids. Thus, SRI estimates that continued improvement in this area prior to development will require a small effort at a cost of $0.2 million.

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* TRW Structures Division, Cleveland, Ohio, under Contract NASw-6555; Aeronutronic, Division of Philco-Ford, is also investigating this problem.

Advanced Solid Motors

In the case of advanced, single-impulse solid motors containing beryllium propellant, considerable progress has been made in research and development in virtually all areas of concern over the past eight years (Refs. 11-16). Toxicity problems are considered less serious than once anticipated (Ref. 14), nozzle materials within the state of the art have been shown to be more acceptable than previous experience indicated (Ref. 15), and facilities for manufacture and testing are now available (Ref. 16). Furthermore, almost all the major propulsion companies have had experience in loading and firing beryllium motors.* Despite the fact that certain propellant formulations appear to be less suitable than expected, the general state of the art may be stated as applicable immediately to the upper stage, single impulse motors exhibited in the Lockheed study. On the basis of these observations, $0.5 million is estimated to be required for technology improvement in this area, particularly for propellant characterization.

RSVP Motors

Technology improvement for the RSVP motor is also estimated to require $0.5 million as shown in Table 4. In this case, problems are considered to be somewhat less severe than those encountered in hybrid development, primarily because the RSVP motor does not operate under quite as severe conditions of temperature and generally does not produce such highly corrosive and erosive exhaust products. As indicated in References 3 and 17, problems to be solved are minor if currently conceived systems are used. Research is proceeding in the area of propellants to achieve higher burning rate exponents, to continue study of combustion phenomena, and to demonstrate rapid response on/off capabilities.

Additional Considerations Prior to or During Development

The above problems appear to be the major ones remaining in preliminary work leading to hybrid, solid and RSVP development in motors of the type identified. Other serious problems may arise as development proceeds, however, depending upon the type of program which is initiated. For example, no conclusive evidence of scalability to larger diameter thrust chambers has yet been demonstrated, although efforts are underway in that direction for the hybrid (Ref. 18). Very little work has been undertaken in investigating flight weight liquid storage and delivery systems in the hybrid or RSVP upper stage applications; only one program to date has a flight program scheduled to investigate flight characteristics of a hybrid motor (Ref. 19); and no flights at all are scheduled

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* Each of the propulsion manufacturers visited during the study has remote mixing and handling facilities available, and several also have remote testing sites available on a standby basis.

to investigate flight characteristics of RSVP or beryllium-augmented solid propulsion systems. These deficiencies must be relieved either prior to or during the development programs outlined below.

MOTOR, STAGE AND VEHICLE DEVELOPMENT

Program Assumptions

To establish a basis for estimating RDT&E costs for the propulsion systems under consideration, SRI formulated development programs for each propulsion type as shown in Table 5. These programs were formulated for hybrid, advance solid, wafer-solid, and RSVP motors.

Table 5

MOTOR DEVELOPMENT PROGRAM ASSUMPTIONS
(Number of Units)

	Devel- opment	PFRT	Qualifi- cation	Total
Hybrid Motor Program				
Thrust chamber assemblies	10	6	5	21
Oxidizer assemblies	5	6	5	16
Advanced-solid Motor Program	8	6	6	20
Wafer-solid Motor Program	15	10	6	31
RSVP Motor Program				
Thrust chamber assemblies	10	6	5	21
Liquid system assemblies	5	6	5	16

Source: Stanford Research Institute.

Hybrid Motor Program

A development program of 10 motors is assumed for all hybrid motors--ranging in size from 2,000 to 14,000 pounds--evaluated in this part of the study. The oxidizer delivery systems of these motors are assumed to be reusable; thus, only five of these assemblies are estimated for development testing. Six additional complete systems are estimated for preflight rating tests (PFRT) and five systems for qualification, or a total of 21 thrust chamber assemblies and 16 oxidizer assemblies for the entire program.

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It is recognized that considerable effort will be needed to optimize the design of the oxidizer system. SRI assumes that these design efforts will be included in the development program.

Advanced Solid Motor Program

Development of a beryllium-loaded solid rocket motor is basically within the state of the art, as indicated in the previous chapter. The advantages of such a motor depend to a great extent on its efficiency, however, and considerable effort will be required for optimization. These considerations lead to a motor development program that assumes only slightly less effort than that required for the hybrid motor. Development efforts are estimated to require 8 units; PFRT, 6 units; and qualification, 6 units; or a total program of 20 units as shown in Table 5.

Wafer-solid and RSVP Motor Programs

Development program plans for the wafer-solid motors investigated by Douglas and for the RSVP motor studied by Lockheed are also indicated in Table 5. In the wafer-solid program, 15 units are estimated for development, 10 for PFRT and 6 for qualification. RSVP program assumptions are identical to those for the hybrid motors--that is, 10 thrust chamber assemblies and 5 liquid system assemblies for development, 6 complete units for PFRT, and 5 units for qualification.

In general, development costs for these motors are still considered to be speculative. Neither type has clearly indicated gaps in the state of the art; however, experience has already revealed problem areas in full scale development efforts on wafer-solids. This factor is taken into consideration in estimating a larger number of motors for this program. Although the RSVP concept has yet to be demonstrated fully, it is felt that extrapolation to such motor sizes is possible, because RSVP thrust chambers bear a close resemblance to single-impulse solid motors having the same propellant weight. Requirements for liquid control systems for the RSVP motors have been estimated on the same basis used in estimating oxidizer system components for the hybrid motor.

Development Costs

Motor Development

Development costs were estimated for each motor type, as a function of propellant weight for hybrid thrust chamber and single-impulse solid and as point estimates for hybrid oxidizer systems and wafer-solid and RSVP motors. These costs are summarized in Table 6.

Table 6

MOTOR DEVELOPMENT COSTS
(Dollars in Millions)

Motor Type	Upper Stage Application	Propellant Weight (lb)	Thrust Chamber or Solid Motor Cost*	Liquid System Cost	Total Cost
Hybrid	Third stage Delta	2,000	$ 3.9	$ --	$ --
	Third stage Agena	5,000	4.9	10.7	15.6
	Second stage Delta	10,000	6.2	--	--
	Second stage Agena	14,000	6.8	15.7	22.5
Single impulse solid	Third stage Agena	1,000	4.3	0	4.3
	--	2,000	5.4	0	5.4
	Third stage Agena	5,000	7.5	0	7.5
	--	7,000	8.6	0	8.6
Wafer-solid	Fourth stage Scout	650	6.5	0	6.5
	Third stage Agena	2,000	14.0	0	14.0
RSVP	Third stage Agena	5,500	6.3	8.1	14.4

* Includes estimate for technology improvement.

Source: Stanford Research Institute.

Development costs for hybrid thrust chamber assemblies are estimated to range from $3.9 million for a motor having a total propellant weight of 2,000 pounds, to $6.8 million for a motor having a propellant weight of 14,000 pounds. These weights represent motors sized for third stage Delta and second stage Agena applications, respectively. Thrust chambers for motors having a propellant weight of 5,000 pounds and sized for third stage Agena applications are estimated to cost $4.9 million for development, and thrust chambers for second stage Delta applications (total propellant weight of 10,000 pounds) are estimated to cost $6.2 million for development.

Oxidizer storage and delivery system development costs were estimated for the motors having propellant weights of 5,000 and 14,000 pounds. These costs are $10.7 million and $15.7 million, respectively, making a total of $15.6 million and $22.5 million for these two motors.

Cost estimates were made for advanced single-impulse solid motors having propellant weights of from 1,000 to 7,000 pounds. The smallest of these motors is sized for the solid injection stage over Agena, used in launch vehicle LV-8. Development costs for this motor are estimated to be $4.3 million. The 7,000-pound motor was originally optimized for the third stage Agena for the Asteroid mission but was later revised to 5,000 pounds (Ref. 2). Costs were also estimated for the larger motor, however, to establish another point of reference for the study. Development costs are estimated to be $7.5 million for the 5,000-pound motor and $8.6 million for the 7,000-pound motor.

The two wafer-solid motors designed by Douglas for fourth stage Scout and third stage Delta were also evaluated. These motors have propellant weights of 650 and 2,000 pounds and are estimated to cost $6.5 million and $14 million, respectively. These estimates are more conservative than the figures used by Douglas in its systems study (Ref. 1), primarily because of more recent experience in developing similar motors.

Finally, the thrust chamber for the RSVP motor for Agena kick stage applications, which has a propellant weight of 5,500 pounds, is estimated to require $6.3 million for development. Costs for the control fluid storage and delivery system for this motor are estimated to be $8.1 million. Thus, total development costs for this motor are projected to be $14.4 million.

Stage Development

Total stage development costs were assembled, using the estimates for the appropriate motor sizes and estimates of stage development and integration provided by Lockheed (Ref. 4). These costs are summarized in Table 7 and given in detail in Table A-1. In these tables, flight test hardware--including launch vehicle booster requirements and launch support services provided by the contractors are included in each column on the assumption that the development programs are mutually exclusive and each must bear the total cost of its own flight test program.

Total cost figures indicated in Table 7 are: $51 million for hybrid second stage development plus $25 million for flight test booster hardware and launch services; $37 million for hybrid kick stage development plus $37 million for testing vehicles and launch services; $23 million for solid kick stage development plus $37 million for testing; $19 million for solid injection stage development plus $39 million for testing;* and $32 million for RSVP kick stage development plus $37 million for testing. Breakdowns of each of these figures by propulsion development, stage development and integration, tooling, GSE, flight test operations and planning and management are shown in the table.

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* As indicated in the following section, slight differences occur in launch vehicle costs for third stages, depending on the mission. The costs are: $37 million for the Asteroid mission and $39 million for the synchronous orbit mission.

Table 7

RDT&E SUMMARY BY STAGE
(millions of dollars)

Cost Element	Hybrid Second Stage	Hybrid Kick Stage	Solid Kick Stage	Solid Injection Stage	RSVP Kick Stage
Designation of completed launch vehicle	LV-5	LV-2	LV-1	LV-8	LV-9
Propulsion design and development					
Thrust chamber or solid motor	$ 6.8	$ 4.9	$ 7.5	$ 4.3	$ 6.3
Support structure, oxidizer, assembly, and pressurization system	15.7	10.7	3.6	3.6	8.1
Stage development and integration	12.4	8.7	3.6	3.5	6.7
Tooling and STE	0.8	0.6	0.4	0.4	0.5
Stage GSE	0.3	0.2	0.2	0.2	0.2
Flight test operations					
Engineering support	3.0	2.3	0.8	0.8	2.0
Flight hardware	8.7	7.0	6.4	5.1	6.8
Planning and management	3.4	2.4	1.0	1.0	2.0
Subtotal	$51.1	$36.8	$23.5	$18.9	$32.6
Launch vehicle procurement and launch services	25.1	37.2	37.2	39.1	37.2
Total	$76.5	$74.0	$60.7	$58.0	$69.8

Source: Stanford Research and Lockheed Missiles and Space Company.

Vehicle Development

Total vehicle RDT&E costs for each of the 10 vehicles in the study are summarized in Table 8, with launch vehicle costs again charged to each configuration. Also shown in this table are first unit procurement and launch costs and cumulative average costs for 60 and 120 launches, projected at 95% and 90% learning reductions, respectively.

Total RDT&E costs vary from $58 million for the SLV3X/Agena/solid vehicle (LV-8) to $113 million for the SLV3X/hybrid/hybrid vehicle (LV-7). In this case, it is assumed that both upper stages will be tested together during the flight test program; thus, launch vehicle costs are for five SLV3X boosters and their related launch services.

It is also assumed that SLV3X Agena development costs have been absorbed by other programs; thus, there would no RDT&E costs for launch vehicle LV-3. Slight differences in launch vehicle costs for the SLV3X Agena booster in the two missions result from requirements for hardware peculiar to the mission. The estimated costs are $37.2 million for the Asteroid mission and $39.1 million for the synchronous orbit mission, as shown in Table 8.

Total RDT&E costs for other vehicles used in the synchronous orbit mission are $75.9 million for the LV-4 vehicle (SLV3X/Agena/hybrid); $95.1 million for the LV-6 vehicle (SLV3X/hybrid/solid); and $71.7 million for the LV-10 vehicle (SLV3X/Agena/RSVP).

The cost of the first operational launch of each of the ten vehicles is shown by stage, including SLV3X and Agena which are identified separately. Hardware and launch costs for the SLV3X are estimated to be $5.02 million. For the Agena, these costs are $2.41 million with a third stage above it in the Asteroid mission; $2.8 with a third stage above it in the synchronous mission; and $3.16 million without a third stage. These differences, as shown in detail in Table A-2, are the result of two items: (1) mission peculiar hardware and (2) guidance costs for Agena. When a third stage is added, guidance costs are charged to the third stage.

Hybrid second stage and launch costs are $2.23 million including guidance and $1.87 million without guidance. Third stage first unit costs vary from $1.12 million for the solid injection stage to $1.77 million for the hybrid kick stage, including guidance.

Total first unit costs for these vehicles thus vary from the least costly SLV3X/hybrid at $7.2 million to the most costly SLV3X/Agena/hybrid at $9.6 million. Cumulative average costs for 60 launches are $6.2 million for the SLV3X/hybrid and $8.4 million for the SLV3X/Agena/hybrid. At 120 launches the costs become $5.1 million and $7 million, respectively. Extensive supporting detail for the figures in Table 8 are given in the appendix.

Table 8
COST SUMMARY BY LAUNCH VEHICLE
(Millions of Dollars)

Cost Element	LV-1	LV-2	LV-3	LV-4	LV-5	LV-6	LV-7	LV-8	LV-9	LV-10
RDT&E										
Second stage	$ --	$ --	$ --	$ --	$ 51.1	$ 51.1	$ 51.1	$ --	$ --	$ --
Third stage	23.5	36.8	--	36.8	--	18.9	36.8	18.9	32.6	32.6
Subtotal	$ 23.5	$ 36.8	$ 0	$ 36.8	$ 51.1	$ 70.0	$ 87.9	$ 18.9	$ 32.6	$ 32.6
Launch Vehicle Cost	37.2	37.2	--	39.1	25.1	25.1	25.1	39.1	37.2	39.1
Total RDT&E	$ 60.7	$ 74.0	$ 0	$ 75.9	$ 76.2	$ 95.1	$113.0	$ 58.0	$ 69.8	$ 71.7
Cost of first launch										
First stage and launch	5.020	5.020	5.020	5.020	5.020	5.020	5.020	5.020	5.020	5.020
Second stage and launch	2.410	2.410	3.160	2.800	2.229	1.869	1.869	2.800	2.410	2.800
Third stage and launch	1.367	1.770	--	1.770	--	1.123	1.770	1.123	1.749	1.749
Total launch	$8.797	$9.200	$8.180	$9.590	$7.249	$8.012	$8.659	$8.943	$9.179	$9.569
Average cost for 60 launches										
First stage and launch	4.260	4.260	4.260	4.260	4.260	4.260	4.260	4.260	4.260	4.260
Second stage and launch	2.170	2.170	2.880	2.520	1.975	1.615	1.615	2.520	2.170	2.520
Third stage and launch	1.208	1.590	--	1.590	--	1.012	1.590	1.012	1.573	1.573
Total cost/launch	$7.638	$8.020	$7.140	$8.370	$6.235	$6.887	$7.455	$7.792	$8.003	$8.353
Average Cost for 120 launches										
First stage and launch	3.390	3.390	3.390	3.390	3.390	3.390	3.390	3.390	3.390	3.390
Second stage and launch	1.890	1.890	3.560	2.220	1.683	1.323	1.323	2.220	1.890	2.220
Third stage and launch	1.024	1.383	--	1.383	--	0.885	1.383	0.885	1.371	1.371
Total cost/launch	$6.304	$6.663	$5.950	$6.993	$5.073	$5.598	$6.096	$6.495	$6.651	$6.981

Source: Stanford Research Institute and Lockheed Missiles and Space Company.

COST-EFFECTIVENESS ANALYSIS

Usage Rates and Other Assumptions

In translating the cost figures presented in previous chapters into cost-effectiveness, it is necessary not only to determine payload capabilities of each vehicle, but also to determine a reasonable launch schedule for their use. Total delivered payload must be computed for an assumed period of operations, and total recurring and nonrecurring costs to deliver the payload must be determined. The assumptions used to facilitate these calculations are summarized in Table 9.

Table 9

COST-EFFECTIVENESS ASSUMPTIONS

Usage rates	2/year	6/year	12/year
Learning curves	100%	95%	90%
Recurring (operations) cost	Cost per launch from Table 8 times total launches at each usage rate		
Nonrecurring RDT&E cost	Total RDT&E from Table 8		
Payload (effectiveness)	Payload in orbit for synchronous earth orbit mission; payload at 42,800 ft/sec for Asteroid flythrough mission (from References 2 and 3)		
Total launches	20	60	120
Operational period	10 years		
Operational cost-effectiveness	Operations cost/total delivered payload		
Total cost	Total cost/total delivered payload		

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The study uses as a base for usage rate assumptions, present NASA/OSSA (Office of Space Science and Applications) expectations for launch vehicle procurement as given in the OSSA Prospectus (Ref. 20). It was beyond the scope of this study to examine each of the missions proposed for the Agena and either (1) to determine which missions would benefit most from the use of uprated hybrid or solid augmented Agena vehicles or (2) to establish an optimum pattern for the use of the new vehicles, assuming that all missions would benefit equally.

Alternatively, two launch vehicle schedules have been assumed that generally bracket the minimum and maximum use rates currently projected for Agena during the 1972-86 period. The schedules are 6 and 12 per year for a 10-year period, or alternatively, 4 and 8 per year for the 15-year period given above.

Conservative estimates were made for cost reductions because of learning for these use rates. At 6 units per year, a learning factor of 95% was assumed and at 12 units per year, a learning factor of 90% was assumed. Although even these assumptions would possibly be optimistic at the 4 and 8 per year rates, it will be shown that they do not materially influence the results of the study.

As a check on the latter conclusion, calculations were made for a total of 20 units--2 launches per year--with no reduction in learning assumed. Although this assumption affects the magnitude of the cost-effectiveness figures, the relative position of each vehicle with respect to the others is maintained, as shown in later illustrations.

In deriving the cost-effectiveness figures, calculations were made on the basis of total launches over a 10-year period. Total delivered payload was computed using payload capabilities provided in References 2 and 3. Operations costs were calculated by extending the first unit and average cost figures presented in Table 8 to 20, 60, and 120 total launches, respectively. Operational cost-effectiveness was calculated by dividing operations cost by payload; total cost-effectiveness is the ratio of total program cost, including RDT&E, to payload.

Study Results

Results of the cost-effectiveness calculations are summarized in Tables 10 through 14. The tables are organized primarily by vehicle type, showing the capabilities of each new vehicle in the two primary missions, Asteroid flythrough and 24-hour synchronous earth orbit. Two exceptions to this are noted: (1) current Agena and second stage hybrid vehicles are compared in Table 13, and (2) SLV3X/hybrid/hybrid and SLV3X/hybrid/solid vehicles are compared in Table 14. In each of these cases, the comparisons are made for the synchronous orbit mission only.

From Table 10 operational cost-effectiveness for the SLV3X Agena with a hybrid third stage is $8,000 per pound of delivered payload in

Table 10

COST-EFFECTIVENESS OF SLV3X/AGENA/HYBRID VEHICLES

	Asteroid Mission (launch vehicle LV-2)			Synchronous Orbit Mission (launch vehicle LV-4)		
Launch weight (lb)		308,257			308,864	
Payload weight (lb)		1,140			1,747	
Number of launches	20	60	120	20	60	120
Total delivered payload (lb x 10^{-3})	22.8	68.4	136.8	34.9	104.8	209.6
Program cost (millions of $)						
RDT&E	$ 74.0	$ 74.0	$ 74.0	$ 75.9	$ 75.9	$ 75.9
Operations	184.0	481.2	799.5	191.8	502.2	839.2
Total	$258.0	$555.2	$873.5	$267.7	$578.1	$915.1
Operational cost-effectiveness ($/lb payload)	$8,070	$7,035	$5,844	$5,489	$4,792	$4,004
Total cost-effectiveness ($/lb payload)	$11,316	$8,116	$6,385	$7,662	$5,516	$4,366

Source: Stanford Research Institute.

Table 11

COST-EFFECTIVENESS OF SLV3X/AGENA/SOLID VEHICLES

	Asteroid Mission (launch vehicle LV-1)			Synchronous Orbit Mission (launch vehicle LV-8)		
Launch weight (lb)		307,451			303,242	
Payload weight (lb)		823			1,054	
Number of launches	20	60	120	20	60	120
Total delivered payload (lb x 10^{-3})	16.5	49.4	98.8	21.1	63.2	126.5
Program cost (millions of $)						
RDT&E	$ 60.7	$ 60.7	$ 60.7	$ 58.0	$ 58.0	$ 58.0
Operations	175.9	458.3	756.5	178.9	467.5	779.4
Total	$236.6	$519.0	$817.2	$236.9	$525.5	$837.4
Operational cost-effectiveness ($/lb payload)	$10,661	$9,277	$7,657	$8,478	$7,397	$6,161
Total cost-effectiveness ($/lb payload)	$14,339	$10,506	$8,271	$11,227	$8,315	$6,620

Source: Stanford Research Institute.

Table 12

COST-EFFECTIVENESS OF SLV3X/AGENA/RSVP VEHICLES

	Asteroid Mission (launch vehicle LV-9)			Synchronous Orbit Mission (launch vehicle LV-10)		
Launch weight (lb)		308,279			308,814	
Payload weight (lb)		825			1,360	
Number of launches	20	60	120	20	60	120
Total delivered payload (lb x 10^{-3})	16.5	49.5	99.0	27.2	81.6	163.2
Program cost (millions of $)						
RDT&E	$ 69.8	$ 69.8	$ 69.8	$ 71.7	$ 71.7	$ 71.7
Operations	183.6	480.2	798.1	191.4	501.2	837.7
Total	$ 253.4	$ 550.0	$867.9	$263.1	$572.9	$909.4
Operational cost-effectiveness ($/lb payload)	$11,127	$ 9,701	$8,062	$7,037	$6,142	$5,133
Total cost-effectiveness ($/lb payload)	$15,357	$11,111	$8,767	$9,673	$7,021	$5,572

Source: Stanford Research Institute.

Table 13

COST-EFFECTIVENESS COMPARISON OF AGENA AND HYBRID SECOND STAGES

	SLV3X/Agena (launch vehicle LV-3)			SLV3X/Hybrid (launch vehicle LV-5)		
Launch weight (lb)		301,255			303,345	
Payload weight (lb)		580			1,410	
Number of launches	20	60	120	20	60	120
Total delivered payload ($lb \times 10^{-3}$)	11.6	34.8	69.6	28.2	84.6	169.2
Program cost (millions of $)						
RDT&E	$ --	$ --	$ --	$ 76.2	$ 76.2	$ 76.2
Operations	163.6	428.4	714.0	145.0	374.1	608.8
Total	$ 163.6	$ 428.4	$ 714.0	$221.2	$450.3	$685.0
Operational cost-effectiveness ($/lb payload)	$14,103	$12,310	$10,258	$5,141	$4,422	$3,598
Total cost-effectiveness ($/lb payload)	$14,103	$12,310	$10,258	$7,844	$5,323	$4,048

Source: Stanford Research Institute.

Table 14

COST-EFFECTIVENESS OF SLV3X/HYBRID/HYBRID AND SLV3X/HYBRID/SOLID VEHICLES

	SLV3X/Hybrid/Solid (Launch Vehicle (LV-6)			SLV3X/Hybrid/Hybrid (Launch Vehicle LV-7)		
Launch weight (lb)		305,607			312,262	
Payload weight (lb)		1,783			2,320	
Number of launches	20	60	120	20	60	120
Total delivered payload (lb x 10^{-3})	35.7	107.0	214.0	46.4	139.2	278.4
Program cost (millions of $)						
RDT&E	$ 95.1	$ 95.1	$ 95.1	$113.0	$113.0	$113.0
Operations	160.2	413.2	671.8	173.2	447.3	731.5
Total	$255.3	$508.3	$766.9	$286.2	$560.3	$844.5
Operational cost-effectiveness ($/lb payload)	$4,487	$3,862	$3,139	$3,733	$3,213	$2,628
Total cost-effectiveness ($/lb payload)	$7,151	$4,750	$3,584	$6,168	$4,025	$3,033

Source: Stanford Research Institute.

the Asteroid mission and $5,500 per pound of payload in the synchronous mission, if the most conservative assumptions of 20 total launches and no learning are used. If 60 units are launched in 10 years, these figures would be reduced to $7,000 per pound and $4,800 per pound, respectively; at 12 launches per year for 10 years, the figures become $5,800 per pound and $4,000 per pound. When nonrecurring RDT&E costs are included in these calculations, total cost-effectiveness varies from $11,300 per pound to $6,400 per pound for the Asteroid mission and from $7,700 per pound to $4,400 per pound for the synchronous mission, depending on number of launches.

In comparison with these figures, total cost-effectiveness for SLV3X/Agena/solid vehicles (Table 11) varies from $14,300 per pound to $8,300 per pound for the Asteroid mission, and from $11,200 per pound to $6,600 per pound in the synchronous mission. Corresponding figures for RSVP third stage vehicles (Table 12) are $15,300 per pound to $8,700 per pound and $9,700 per pound to $5,600 per pound.

Because the current SLV3X Agena vehicle cannot perform the Asteroid flythrough mission, it is not possible to compare it with the new three stage vehicles in that mission. In the synchronous orbit mission, however, dramatic improvements are evident. For example, Table 13 indicates that total cost-effectiveness for the SLV3X Agena is $14,100 per pound for 20 launches, $12,300 per pound for 60 launches, and $10,300 per pound for 120 launches. These figures are considerably larger than the corresponding ones for all three stage vehicles at every launch rate. Furthermore, cost-effectiveness for vehicles using a new hybrid second stage is still lower: $7,800 per pound to $4,600 per pound for the LV-5 (SLV3X/hybrid); $7,200 per pound to $3,600 per pound for the LV-6 (SLV3X/hybrid/solid); and $6,200 per pound to $3,000 per pound for the LV-7 (SLV3X/hybrid/hybrid).

All of these comparisons are illustrated in Figures 9 and 10, which show total cost-effectiveness in the Asteroid and synchronous orbit missions, respectively, as a function of number of launches. As indicated above, the cost-effectiveness of all vehicles is considerably greater than that for Agena even when the most conservative estimates are used--namely no cost reductions in hardware procurement and a minimum number of vehicles. Figures 9 and 10 also illustrate that the investment in any of the new vehicles would be returned at less than 10 launches, and that the development cost of several of the configurations (hybrid kick stage, for example) would be amortized at less than 5 launches.

Cost-effectiveness of the new vehicles in missions other than those presented above is illustrated in Figures 11 and 12. These figures show total cost-effectiveness as a function of mission velocity evaluated for a program of 120 launches. Figure 11 compares two-stage vehicles, and Figure 12 compares three-stage vehicles.

FIGURE 9

COST-EFFECTIVENESS OF NEW VEHICLES IN ASTEROID MISSION
$\Delta V = 42{,}800$ ft/sec

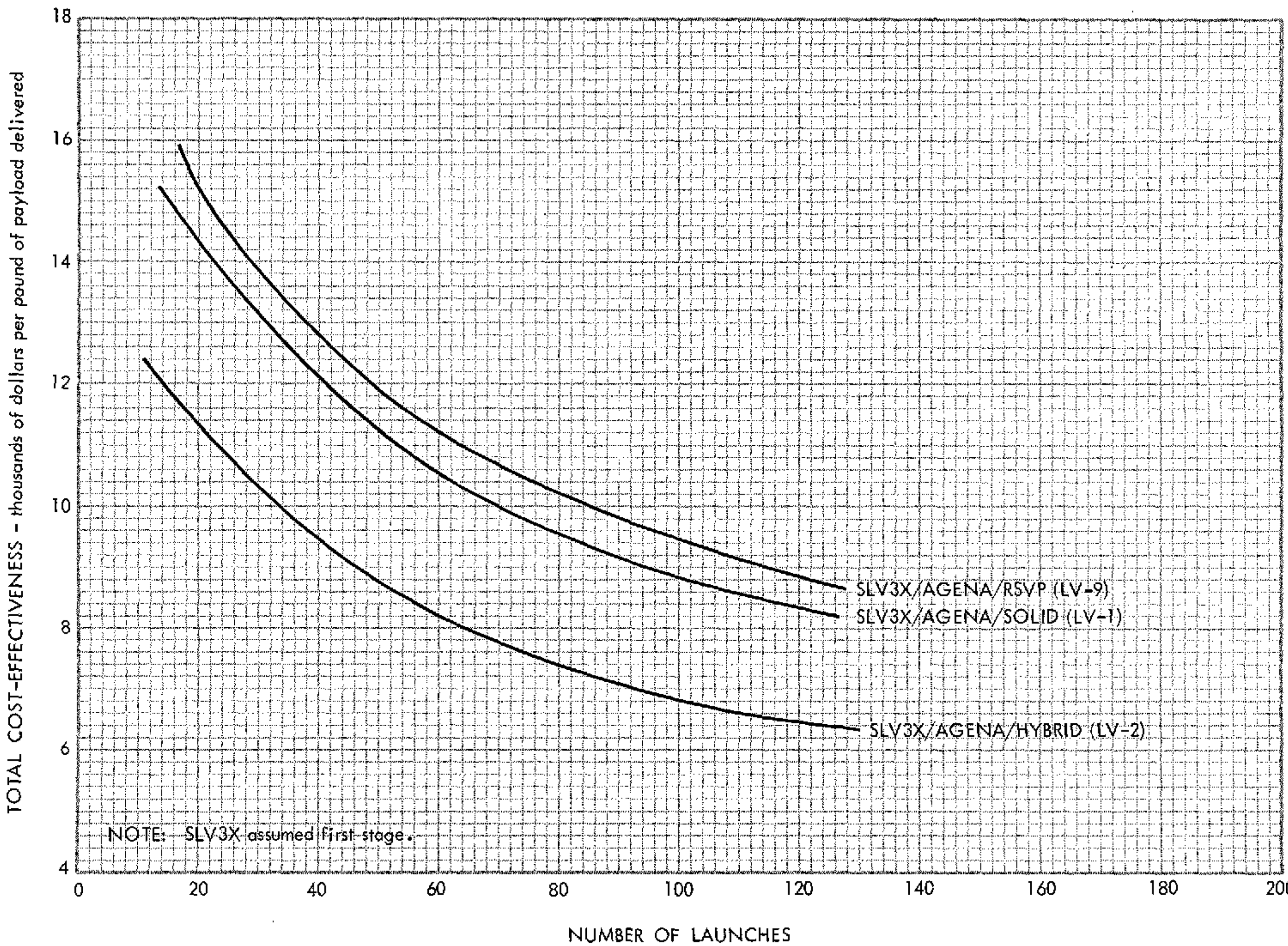


FIGURE 10

COST-EFFECTIVENESS OF NEW VEHICLES IN 24-HR SYCHRONOUS EARTH ORBIT

$\Delta V = 39{,}600$ ft/sec

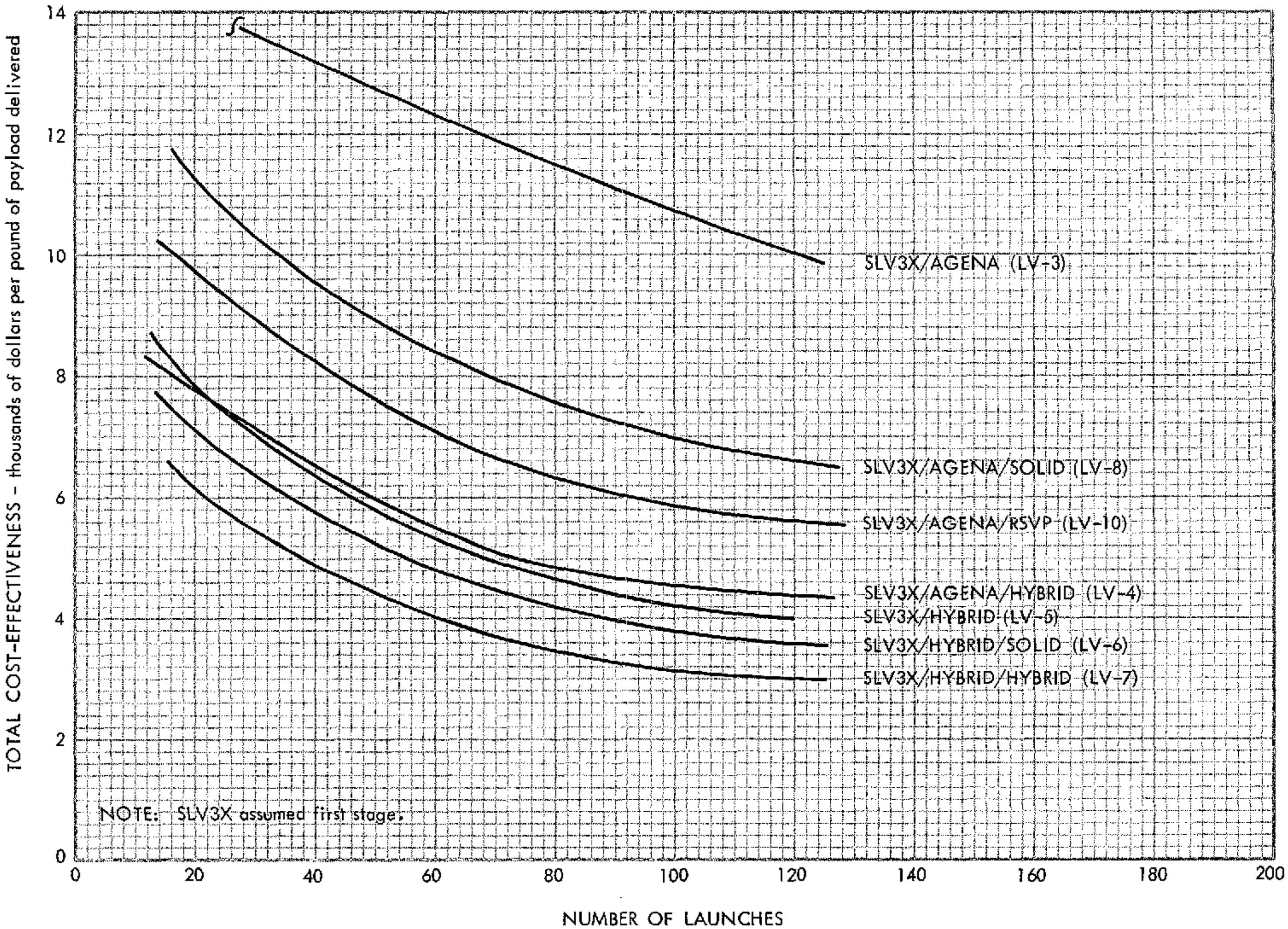


FIGURE 11

COST-EFFECTIVENESS OF AGENA AND NEW HYBRID SECOND STAGE IN OTHER MISSIONS

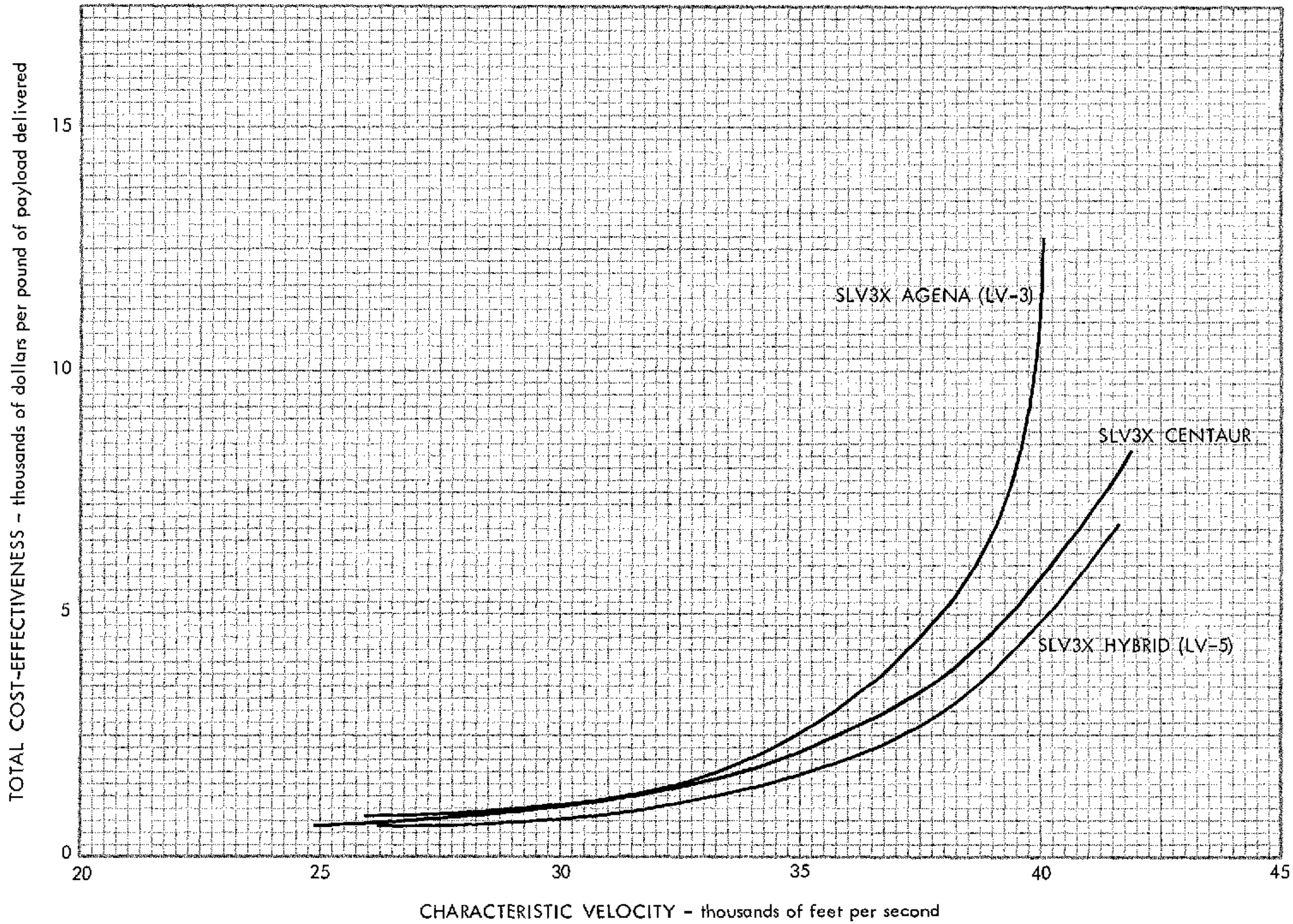
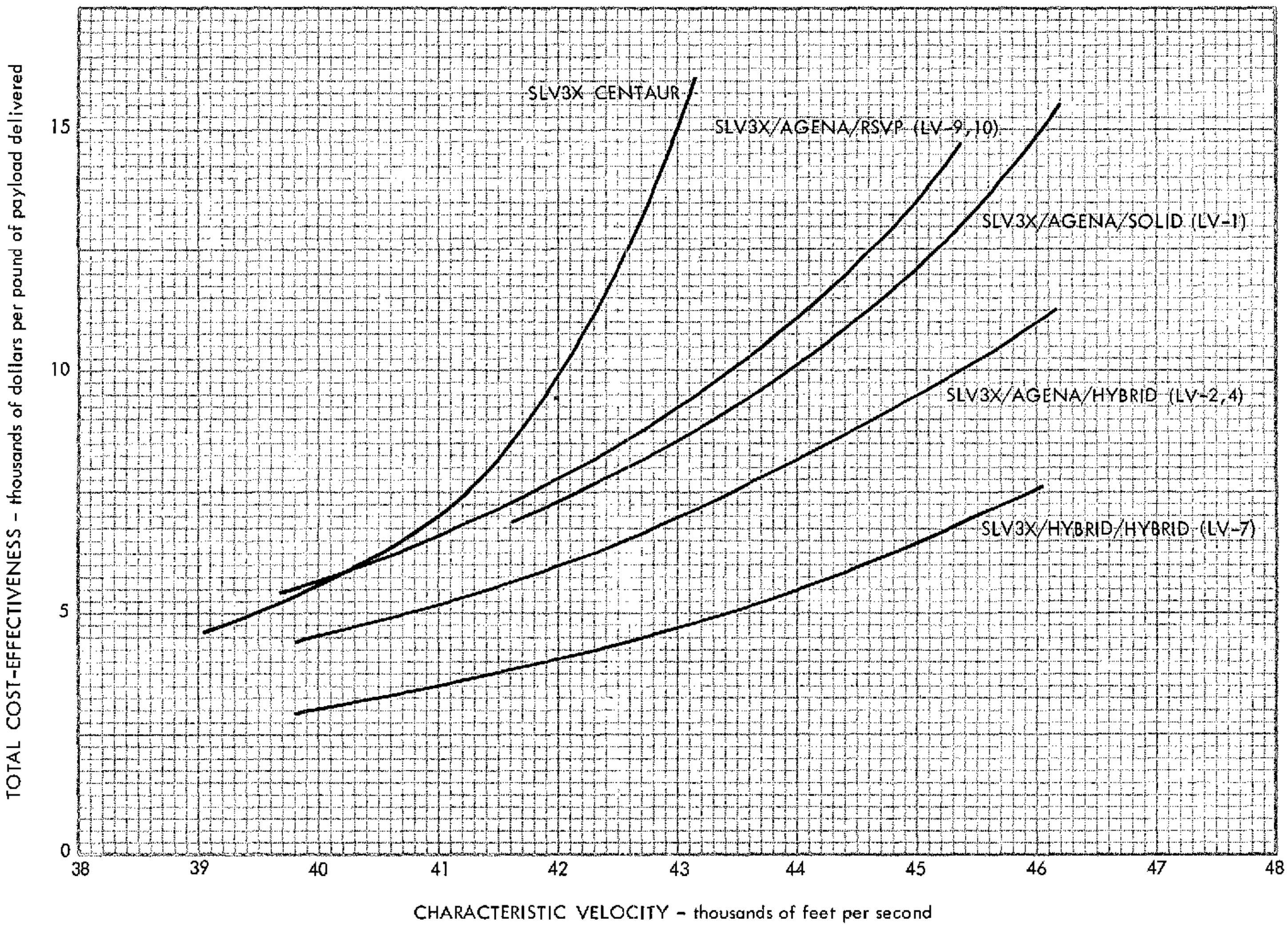


FIGURE 12

COST-EFFECTIVENESS OF NEW HYBRID, SOLID, AND RSVP THIRD STAGES IN OTHER MISSIONS



Again, significant improvement in cost-effectiveness is indicated, especially at the higher velocities. Since the limit of Agena performance is approximately 40,000 ft/sec, this vehicle cannot be compared above that velocity. However, available information on the SLV3X Centaur (Refs. 5 and 6) allows a comparison of that vehicle, and relevant curves are shown on both figures. As indicated in the figures, even this high performance vehicle cannot compete with the new hybrid vehicles, and it is only slightly better than the solid and RSVP vehicles at low velocities. From these results, it is the conclusion of this study that investment in any of the new propulsion systems is feasible from the standpoint of cost-effectiveness.

Part II

SOUNDING ROCKET APPLICATIONS

INTRODUCTION

The approach to determining cost and cost-effectiveness for hybrid, advanced solid, and RSVP propulsion applied to sounding rockets has necessarily been different from the previous analysis for upper stage applications. The principal reason for this divergence is the fact that detailed systems analsyses similar to the Douglas and Lockheed studies have not yet been completed for these applications. Such studies are now in progress, particularly by Space General Corporation as a follow on to a previous study that identified potential gaps in the pattern of payload/altitude capabilities of present vehicles and established preliminary conceptual designs for families of hybrid and advanced solid vehicles for a variety of missions (Ref. 21).

The current SGC study is intended to develop preliminary specifications for new optimum sounding rockets for specific purposes, using several of the propulsion methods discussed herein. It will also investigate potential liquid propulsion vehicles, using more advanced propellants than currently employed. The study will thus result in specific designs that can be analyzed in detail for cost implications.

In the absence of such designs, the approach taken for preliminary cost-effectiveness calculations in the sounding rocket application was as follows:

1. Determine a measure of cost-effectiveness for sounding rocket vehicles analogous to dollars per pound in orbit for larger launch vehicles and upper stages.

2. Calculate the cost-effectiveness of current sounding rockets, using the above measure and using representative costs for which there are available data.

3. Determine performance criteria for families of hybrid and advanced solid sounding rocket vehicle designs for medium and high altitude missions, using data taken from the previously mentioned SGC report.

4. Develop cost data for the new conceptual designs, using a statistical approach based on current vehicle costs.

5. Compute estimated cost-effectiveness for the new designs by combining results of steps 3 and 4.

ANALYSIS OF CURRENT VEHICLES

Determination of Measures of Cost-Effectiveness

In seeking a common point of comparison of new sounding rocket vehicles with those already in use, it is clear that payload and altitude are the key performance parameters, much as payload to a specified orbit or velocity establishes a common base for comparing larger vehicles and upper stages. The significant difference in sounding rockets, however, is that altitudes vary as much as payloads. Thus, it is not particularly convenient to discuss payloads of sounding rockets to a common altitude.

A measure of effectiveness that is more appropriate in these applications, is the product of payload and altitude--pound-miles, for example. This parameter is a consistent measure of performance, since it represents the work done by the rocket in overcoming gravity.

The concept of payload times altitude was used in a recent study by Atlantic Research Corporation that investigated optimum meteoroligical sounding rockets (Ref. 22). In this report, a diagram is given that depicts the performance in pound-miles of current sounding rockets for meteorological use as a function of launch weight of the vehicle. These data--reproduced here in Table 15 and Figure 13--are especially instructive, because they illustrate the fact that almost all successful vehicles in the small to medium class fall within a small range of a straight line plotted on log-log paper. Furthermore, this correlation holds true, according to ARC, for vehicle weights between 30 and 30,000 pounds. Thus, such a correlation line may be termed "approximate state of the art," as ARC suggests.

To verify the above relationship for larger sounding rocket vehicles, data for 18 of the 24 vehicles examined by SGC in its report on Application of Advanced Solid and Hybrid Motors to Soundings Rockets (Ref. 21) were plotted as above. These data are shown in Table 16 and plotted in Figure 14. Again, as shown, a strong correlation exists between launch weight and the product of payload and altitude. This finding suggests, in fact, that the relationship might be used to evaluate the projected performance of new vehicles, and such an analysis is given in later sections.

Cost-Effectiveness of Current Vehicles

The determination of a measure of cost-effectiveness requires both performance and cost. Generally, performance is the easier of these two

Table 15

PERFORMANCE OF ONE-STAGE SOUNDING ROCKETS

Data Point*	Vehicle Name	Weight† (lb)	Listed Performance‡ (lb-mi)
1	Aerobee 150	1,943	150-152
2	Iris	1,250	100-200
3	Tomahawk	585	50-105
4	Black Brant III	630	40-110
5	Thunderbird	445	35-117
6	Archer	330	40-90
7	Asp IV	208	50-50
8	Asp I	216.5	50-35
9	Oriole (dart)	236	10-90
10	Hopi Chaff Dart	93	11.5-57
11	Arcas	65	12-40
12	Raven	100	10-47

* Data points for Figure 13.

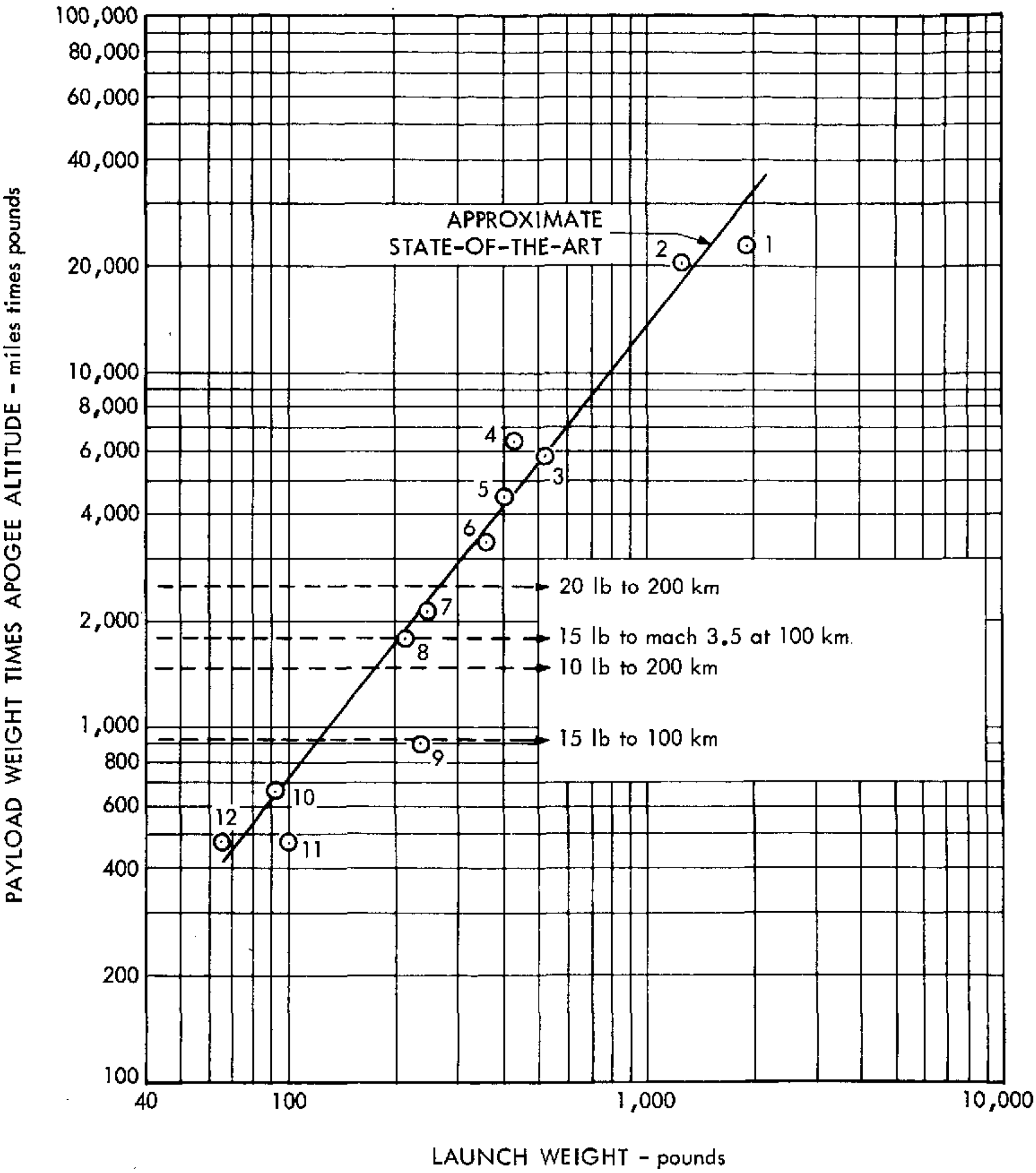
† Minus payload weight.

‡ From Missiles and Rockets, 8th World Missile/Space Encyclopedia, July 27, 1964, pp. 76-80 (Ref. 22).

Source: Atlantic Research Corporation.

FIGURE 13

PAYLOAD TIMES APOGEE ALTITUDE AS A FUNCTION OF LAUNCH WEIGHT FOR ONE-STAGE SOUNDING ROCKETS *



* Vehicles are listed in Table 15.

SOURCE: Atlantic Research Corporation.,

Table 16

PERFORMANCE OF SOUNDING ROCKETS
FOR MEDIUM AND HIGH ALTITUDES

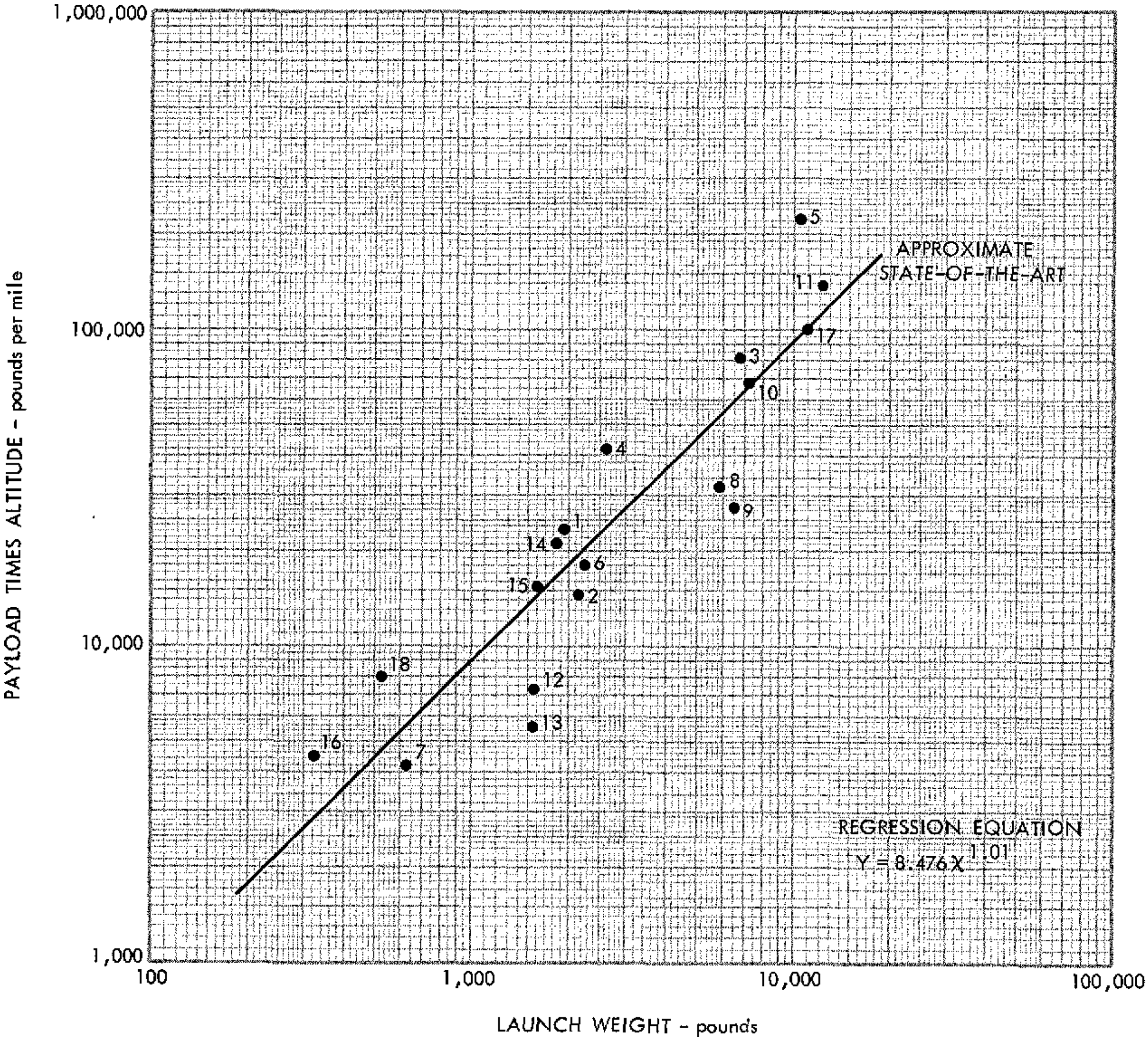
Data Point*	Vehicle Name	Launch Weight (lb)	Payload-Altitude Capability (lb-mi)	Payload X Altitude (lb-mi)
1	Aerobee 150	1,943	150-156	23,400
2	Aerobee 300	2,103	60-246	14,760
3	Aerobee 350	6,800	300-275	82,500
4	Astrobee 200	2,601	300-140	42,000
5	Astrobee 1500	11,541	150-1,500	225,000
6	Black Brant IIA	2,240	200-90	18,000
7	Black Brant III	630	40-105	4,200
8	EXOS	5,821	100-320	32,000
9	Honest John-Nike-Nike	6,500	300-93	27,900
10	Javelin-Argo D4	7,400	125-550	68,750
11	Journeyman	12,110	125-1,100	137,500
12	Nike-Apache	1,550	62-118	7,316
13	Nike-Cajun	1,550	70-80	5,600
14	Nike-Tomahawk	1,850	100-210	21,000
15	Nike-Iroquois (Niro)	1,591	130-120	15,600
16	Phoenix	320	30-150	4,500
17	Shotput-Mod I	11,000	200-500	100,000
18	Tomahawk	531	100-80	8,000

* Data points for Figure 14.

Sources: Technology Week, Tenth Annual World Missile/Space Enclyclopedia, July 25, 1966 (Ref. 24). Space General Corporation.

FIGURE 14

PAYLOAD TIMES ALTITUDE AS A FUNCTION OF LAUNCH WEIGHT
FOR MEDIUM AND HIGH ALTITUDE SOUNDING ROCKETS *



* Vehicles are listed in Table 16.

SOURCE: Stanford Research Institute.

parameters to obtain. However, cost figures acceptable for this preliminary study are available, such as those given by Colin O. Hines in a recent article published in Astronautics & Aeronautics (Ref. 23). These figures are reproduced in Table 17. They are for a variety of vehicles covering a wide range of payload/altitude capabilities. The costs of these vehicles range from $700 per unit for the Indi-Dart meteorological sounding rocket to about $1 million for the Blue Scout Jr. The latter vehicle is capable of, and used extensively for, orbital operations. This capability places it in a somewhat different category from the other sounding rockets, especially from the cost standpoint; the next largest vehicles are the Aerobee 350 and the Journeyman, each at $140,000 per unit.

Table 17

COST OF SELECTED SOUNDING ROCKETS

Existing Rockets	Annual Use	Base Cost	Payload Altitude (kg-km)
Arcas Met Rocket	~2,000	$ ~2,000	5-80
Judi-Dart	~100	~700	2-80
Nike-Cajun	100-200	~6,000	25-120
Nike-Apache	100-200	~6,000	25-160
Black Brant III	10-20	~10,000	20-160
Tomahawk, Hydac	45	~10,000	40-100
Deacon-Arrow or Kisha-Judi	10	2,500	6-110
Nike-Tomahawk	50	15,000	30-300
Nike-Iroquois	(new)	~10,000	20-220
			100-100
Aerobee 150/150A	50-60	~30,000	75-240
			200-120
Aerobee 300		38,000	25-400
Aerobee 350	1	140,000	70-450
Argo D-4 (Javelin)		50,000	45-1,000
Argo D-8 (Journeyman)		140,000	60-1,800
Blue Scout Jr. or equivalent		~1,000,000	?

Source: Astronautics & Aeronautics, January 1966.

If the data in Tables 16 and 17 are combined, operational cost-effectiveness in dollars per pound-mile can be calculated. This is done for 14 of the 15 vehicles listed in Table 17. (Blue Scout Jr. is eliminated because of its much larger size and cost). The results of these calculations are given in Table 18, where it is seen that cost-effectiveness is between $1 and $2 per pound-mile for the most part, with the only exception being the Arcas, which is shown at slightly over $4 per pound-mile.

Using these results, it now becomes clear that we have at least two measures with which to compare sounding rocket vehicles. The first is performance, in terms of the product of payload and altitude. To compete with existing vehicles from a performance standpoint alone, a new vehicle must be capable of achieving at least the state of the art indicated in Figure 14--that is, its nominal payload times altitude must be to the left of the line indicating state of the art. Second, new vehicles may be evaluated for cost-effectiveness in the manner indicated above; if their potential cost-effectiveness is greater than the average for current vehicles, they may be said to be economically feasible. Otherwise, they may be said to be economically infeasible. This approach is used in the following analysis.

Table 18

COST AND COST-EFFECTIVENESS OF CURRENT SOUNDING ROCKETS

Data Point*	Vehicle Name	Launch Weight (lb)	Payload-Altitude (lb-mi)	Payload X Altitude (lb-mi)	Base Cost ($)	Operational Cost-Effectiveness ($/lb-mi)
1	Arcas	65	12-40	480	$ 2,000	$4.17
2	Judi-Dart	34	10-40	400	700	1.75
3	Nike-Cajun	1,550	70-80	5,600	6,000	1.07
4	Nike-Apache	1,550	62-118	7,316	6,000	0.82
5	Black-Brant III	630	40-105	4,200	10,000	2.38
6	Tomahawk	531	100-80	8,000	10,000	1.25
7	Deacon-Arrow	190	20-57	1,140	2,500	2.19
8	Nike-Tomahawk	1,850	100-210	21,000	15,000	0.71
9	Nike-Iroquois (Niro)	1,591	130-120	15,600	10,000	0.64
10	Aerobee 150/150A	1,943	150-156	23,400	30,000	1.28
11	Aerobee 300	2,103	60-246	14,760	38,000	2.57
12	Aerobee 350	6,800	300-275	82,500	140,000	1.70
13	Argo D-4 (Javelin)	7,400	125-550	68,750	50,000	0.73
14	Argo D-8 (Journeyman)	12,110	125-1,100	137,500	140,000	1.02

* Data points for Figure 20.

Source: Stanford Research Institute.

ANALYSIS OF NEW VEHICLES

Performance of New Hybrid and Advanced Solid Designs

Tables 19 and 20 present design summaries for six hybrid sounding rockets that have been extracted from the SGC report (Ref. 21). These designs do not represent completely optimized vehicles for the particular applications for which they are suggested. Rather, they represent families of hybrid vehicles of two basic types--constant thrust, and blowdown or decreasing thrust.

The concepts of these two types of vehicles are illustrated in Figures 15 and 16. The constant thrust system (Fig. 15) uses a gas generator to pressurize the oxidizer, and force it into the thrust chamber. The blowdown system (Fig. 16) utilizes a pre-pressurized oxidizer system, which produces a regressive thrust curve as the pressure in the tank decreases over time.

Figures 17 and 18 illustrate the payload-altitude performance characteristics of the hybrid vehicle designs given above. From these figures, a nominal payload and altitude for each vehicle has been selected. These points are shown on the figures; as indicated, they are approximately midway between the end points of the curves in each case. The points selected are:

Vehicle Designation	Payload	Altitude
A	32	75
B	88	210
C	250	320
A′	42	100
B′	75	200
C′	240	370

In the SGC report, consideration was also given to a family of advanced solid "building block" sounding rockets. A summary of these designs--including typical performance--is shown in Table 21. In this case, a common payload weight of 250 pounds is specified, and performance is shown to vary from 110 miles for a single 16-inch diameter rocket to 768 miles for a three stage vehicle consisting of a 30-inch booster and 22-inch and 16-inch sustainers.

Table 19

H_2O_2- POLYETHYLENE
CONSTANT THRUST SYSTEM WEIGHT BREAKDOWN

	Design		
	A	B	C
Oxidizer			
Usable	1,212.3	884.0	2,830.0
Unusable	4.2	17.7	56.6
Fuel			
Usable	31.7	132.0	422.0
Unusable (includes sliver)	1.9	7.9	25.3
Nitrogen	8.8	36.6	122.0
Nitrogen tank	10.2	40.4	88.7
Oxidizer tank	7.1	29.8	97.8
Oxidizer manifold and injector assembly	1.0	1.2	1.3
Combustion chamber case	3.1	11.8	35.5
Combustion chamber insulation	2.7	6.1	10.8
Grain liner	0.7	1.6	3.9
Nozzle assembly (ε = 6)	3.7	6.9	11.7
Rings and interconnect structure	2.4	5.3	9.7
Pressurization system regulator valves and line	4.3	4.8	6.4
Oxidizer system valve and line	1.4	2.8	4.4
Total weight	295.5	1,189	3,726
Usable propellant	244.0	1,016	3,252
Motor mass fraction	0.825	0.854	0.873

Source: Space General Corporation.

Table 20

H_2O_2- POLYETHYLENE
BLOWDOWN SYSTEM WEIGHT BREAKDOWN

	Design		
	A′	B′	C′
Oxidizer			
Usable	121.0	505	1,613
Unusable	2.4	10.1	32.2
Fuel			
Usable	121.0	505	1,613
Unusable	10.7	30.3	80.7
Nitrogen	12.3	51.3	164.1
Oxidizer tank (including skirts)	18.9	68.6	175.6
Oxidizer injector assembly	0.5	1.0	1.2
Combustion chamber case (including skirts)	16.6	61.6	192.3
Combustion chamber insulation	6.1	6.1	70.8
Grain liner	0.9	5.7	11.1
Nozzle assembly ($\epsilon = 6$)	3.7	6.9	11.7
Rings and interconnect structure	5.3	5.3	10.6
Oxidizer squib valve and line	1.2	2.7	7.0
Total weight	320	1,260	3,923
Usable propellant	242	1,010	3,226
Motor mass fraction	0.753	0.801	0.822

Source: Space General Corporation.

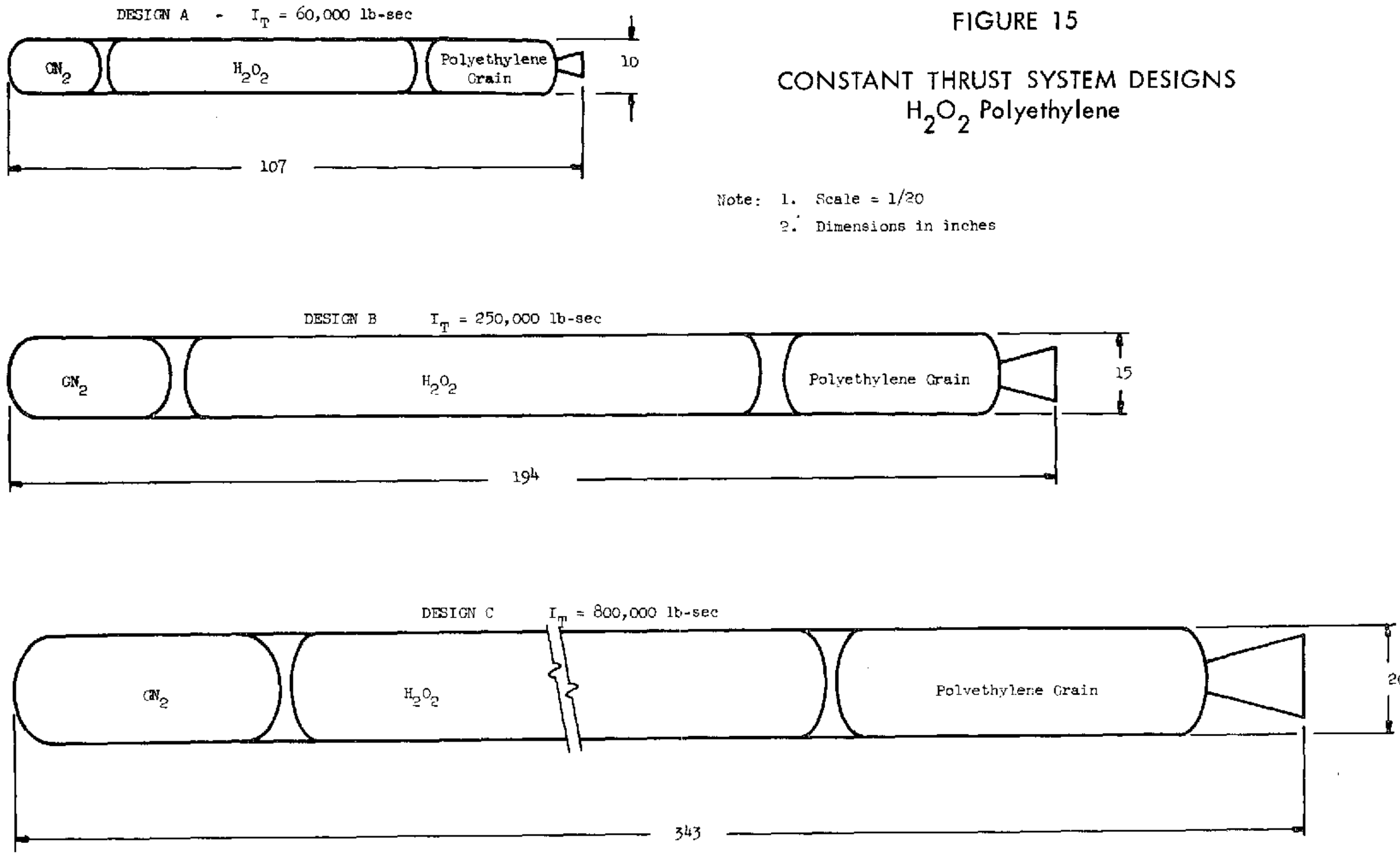


FIGURE 15

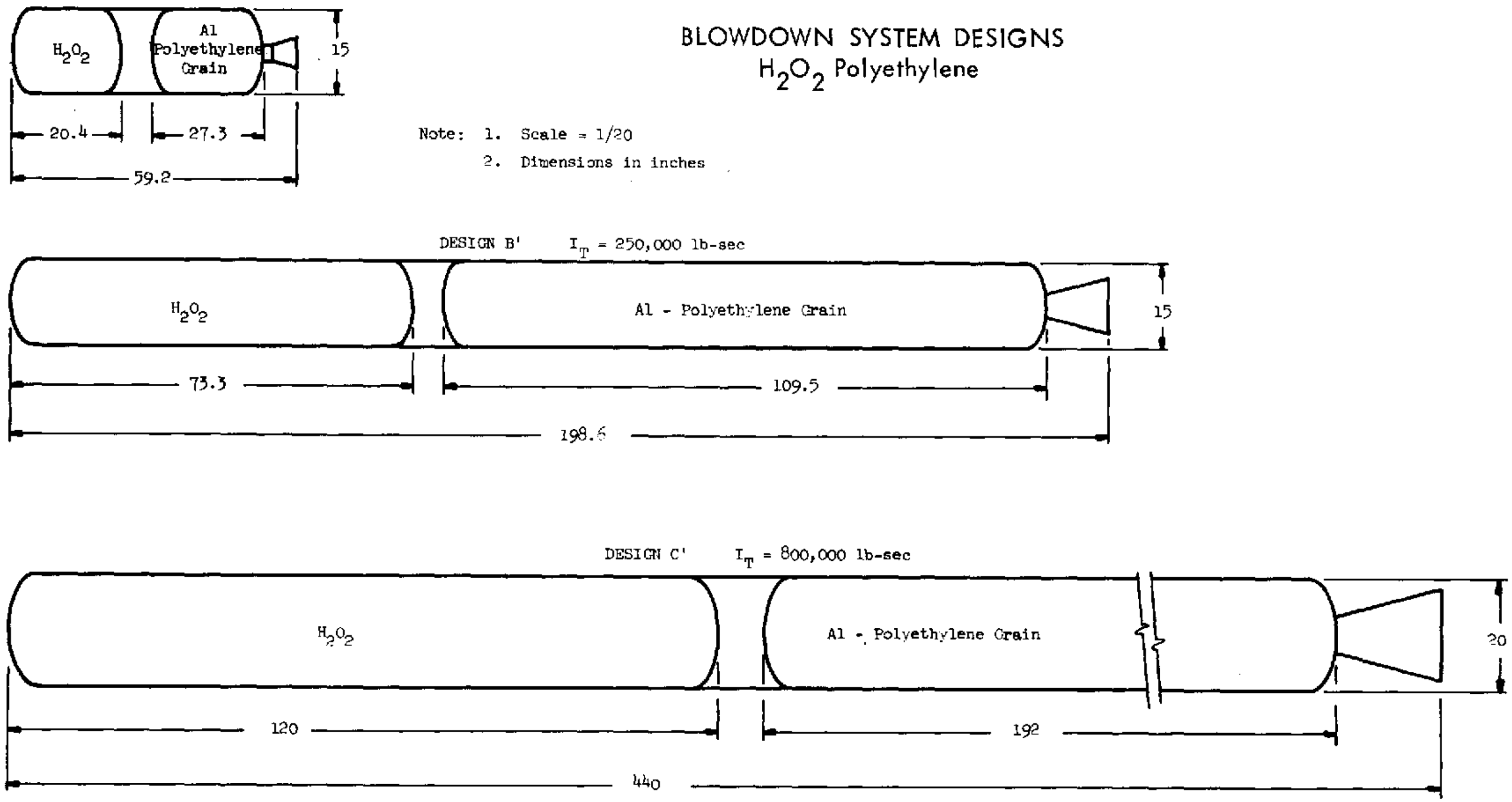
CONSTANT THRUST SYSTEM DESIGNS
H_2O_2 Polyethylene

Note: 1. Scale = 1/20
2. Dimensions in inches

SOURCE: Space-General Corporation.

FIGURE 16

BLOWDOWN SYSTEM DESIGNS
H_2O_2 Polyethylene

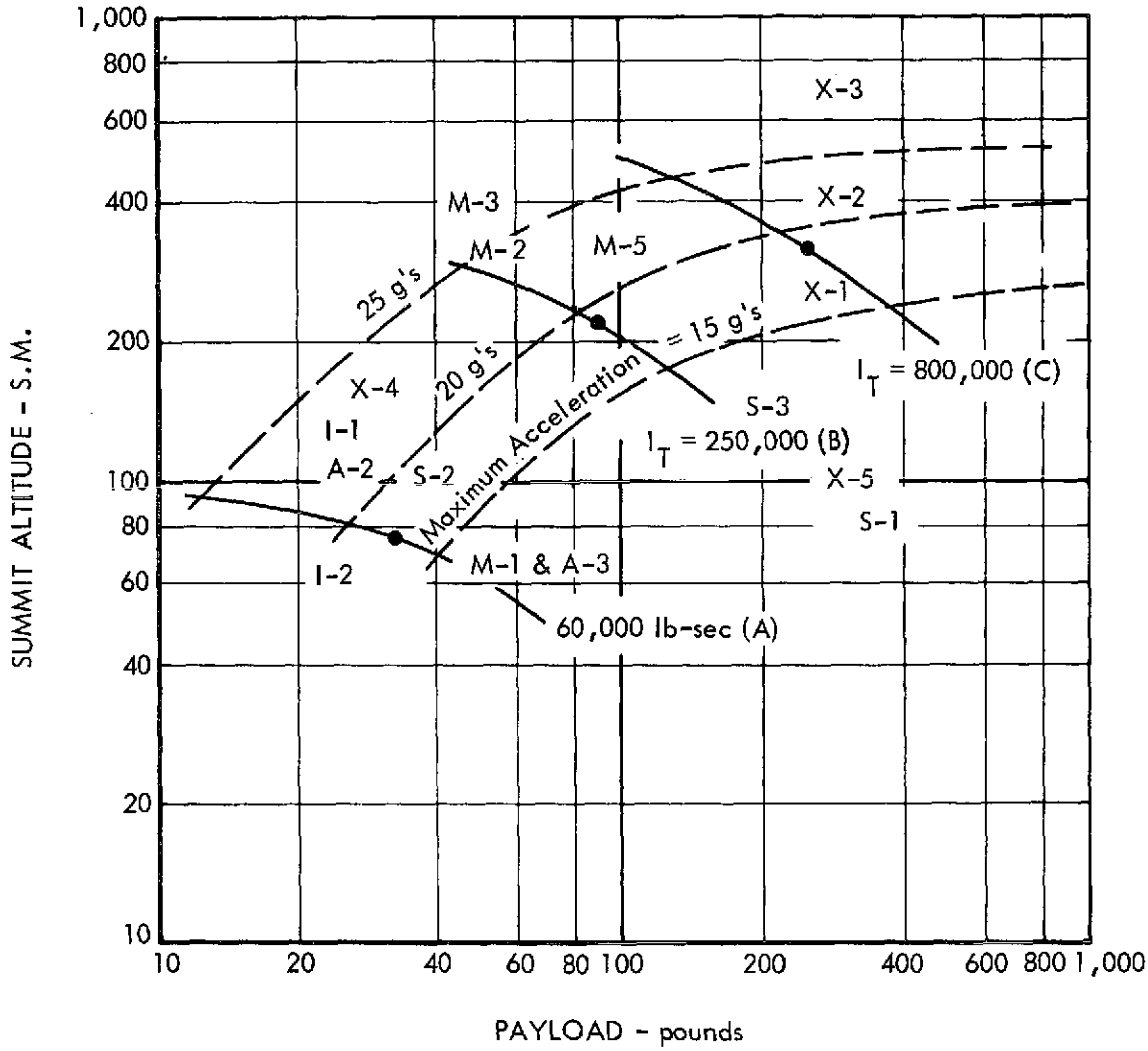


Note: 1. Scale = 1/20
2. Dimensions in inches

SOURCE: Space-General Corporation.

FIGURE 17

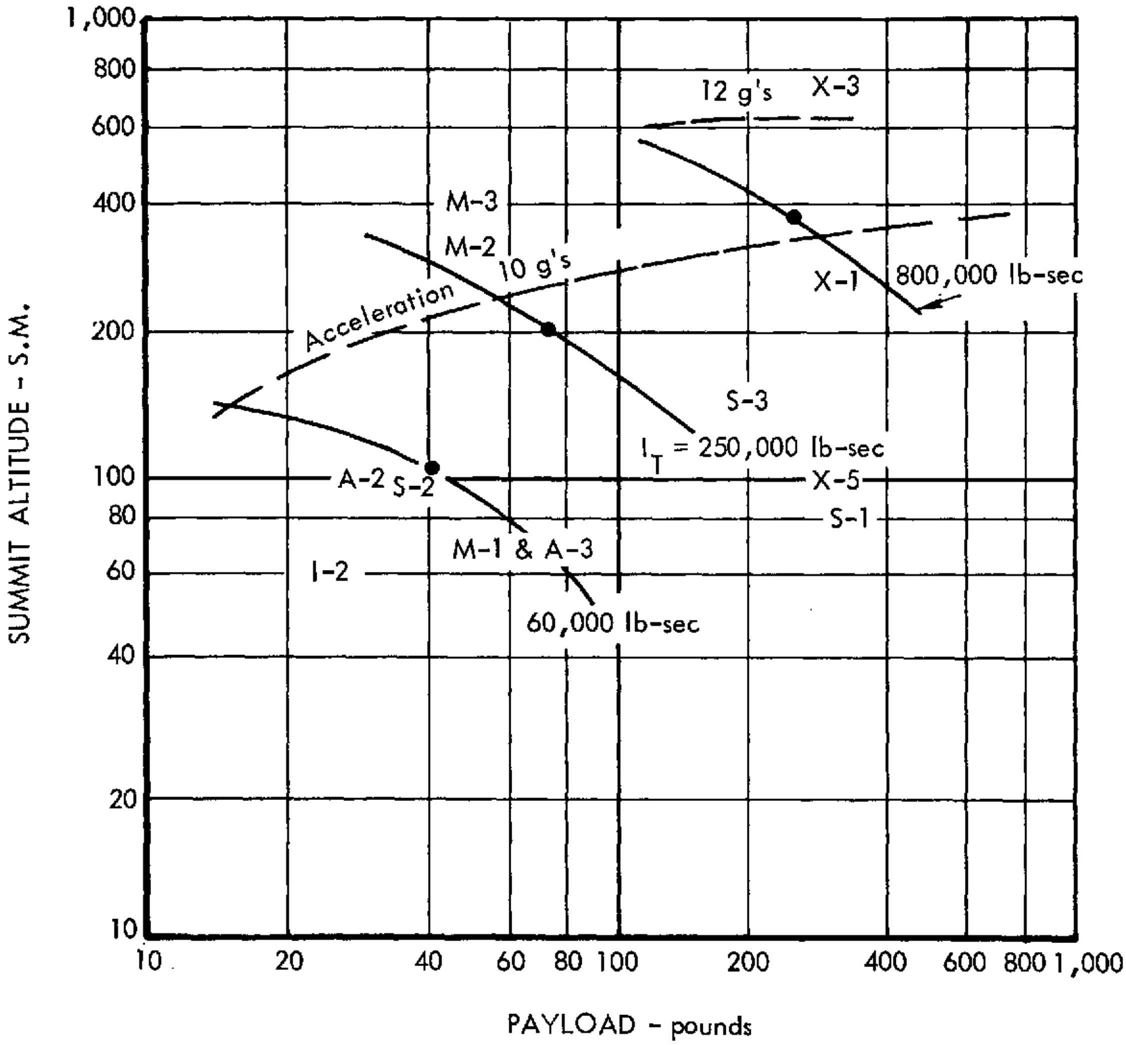
H_2O_2 - POLYETHYLENE CONSTANT THRUST SYSTEM
MISSION CAPABILITIES



SOURCE: Space-General Corporation.

FIGURE 18

H_2O_2 - POLYETHYLENE BLOWDOWN SYSTEM
MISSION CAPABILITIES



SOURCE: Space-General Corporation.

Table 21

SUMMARY OF SOLID ROCKET CONCEPTUAL MOTOR DESIGNS USING THE BUILDING BLOCK TECHNIQUE

Vehicle Number:	2	3	4	5	6	7	1*	2′	3′	4′	5′	6′	7′
Number of Stages:	1	1	2	2	2	3	1	1	1	2	2	2	3
Motor length (in.)													
Stage 1	166.78	125.3	308.58	308.58	166.78	308.58	308.58	260.59	129.77	308.58	308.58	260.59	308.58
Stage 2			166.78	125.3	125.3	166.78				260.59	129.77	129.77	260.59
Stage 3						125.3							129.77
Overall	166.78	125.3	475.36	433.88	292.08	600.66	308.58	260.59	129.77	569.2	438.35	390.36	698.9
Motor diameter (in.)													
Stage 1	22.0	16.0	30.0	30.0	22	30	30.0	22.0	16	30	30	22	30
Stage 2			22.0	16.0	16	22				22	16	16	22
Stage 3						16							16
Weight (lb)													
Stage 1	4,589	1,631	6,026	6,206	4,589	6,026	6,026	4,520	1,506	6,026	6,026	4,520	6,026
Stage 2			4,589	1,631	1,631	4,589				4,520	1,506	1,506	4,520
Stage 3						1,631							1,506
Gross	4,589	1,631	10,615	7,657	6,220	12,246	6,026	4,520	1,506	10,546	7,532	6,026	12,052
Expended	978.39	408	2,183.39	1,613	1,386.4	2,591	1,205	904.86	301.23	2,110	1,506	1,206	2,411
Time of burning (70°F), sec													
Stage 1	47.65	35.8	20.0	20.0	47.65	20	20.0	30.0	30.0	20	20	30	20
Stage 2			47.65	35.8	35.80	47.65				30	30	30	30
Stage 3						35.80							30
Thrust (average - S.L.) LBF													
Stage 1	18,887	8,390	6×10^4	6×10^4	18,887	6×10^4	6×10^4	3×10^4	1×10^4	6×10^4	6×10^4	3×10^4	6×10^4
Stage 2			18,887	8,390	8,390	18,887				3×10^4	1×10^4	1×10^4	3×10^4
Stage 3						8,390							1×10^4
Total impulse (S.L.) lb-sec													
Stage 1	9×10^5	3×10^5	1.2×10^6	1.2×10^6	9×10^5	1.2×10^6	1.2×10^6	9×10^5	3×10^5	1.2×10^6	1.2×10^6	9×10^5	1.2×10^6
Stage 2			9×10^5	3×10^5	3×10^5	9×10^6				9×10^5	3×10^5	3×10^5	9×10^5
Stage 3						3×10^5							3×10^5
Total	9×10^5	3×10^5	2.1×10^6	1.5×10^6	1.2×10^6	2.4×10^6	1.2×10^6	9×10^5	3×10^5	2.1×10^6	1.5×10^6	1.2×10^6	2.4×10^6
Acceleration limits - g's: motor (S) less payload	15-18	18-21	15-18	19-23	18-21	18-21	47-53	32-35	32-35	32-35	32-35	32-35	32-35
Propellant designation	ANB3155	ANB3155	†	†	ANB3155	†	ANB-3066	ANB-3066	ANB-3066	ANB-3066	ANB-3066	ANB-3066	ANB-3066
Grain configuration	End burning	End burning	†	†	End burning	†	Star	Star	Star	Star	Star	Star	Star
Typical performance (lb)	250	250	250	250	250	250		250	250	250	250	250	250
Statute miles	300	110	465	400	352	715		318	125	479	421	368	768

* Booster common to both end-burning and radial-burning solid rocket motor groups.
† Vehicle consists of radial-burning booster and end-burning sustainer(s).

Source: Space General Corporation.

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From the preceding tables and figures, the pertinent information to enable cross-plotting of performance and vehicle weight may be extracted. This information is presented in Table 22. The range of weights extends from 300 pounds to 4,000 pounds for hybrids and from 1,500 pounds to 12,000 pounds for advanced solids. Performance for these vehicles varies from 2,400 to 89,000 pound-miles for hybrids and from 31,000 to 192,000 pound-miles for advanced solids.

Table 22

PERFORMANCE OF HYBRID AND ADVANCED SOLID VEHICLES

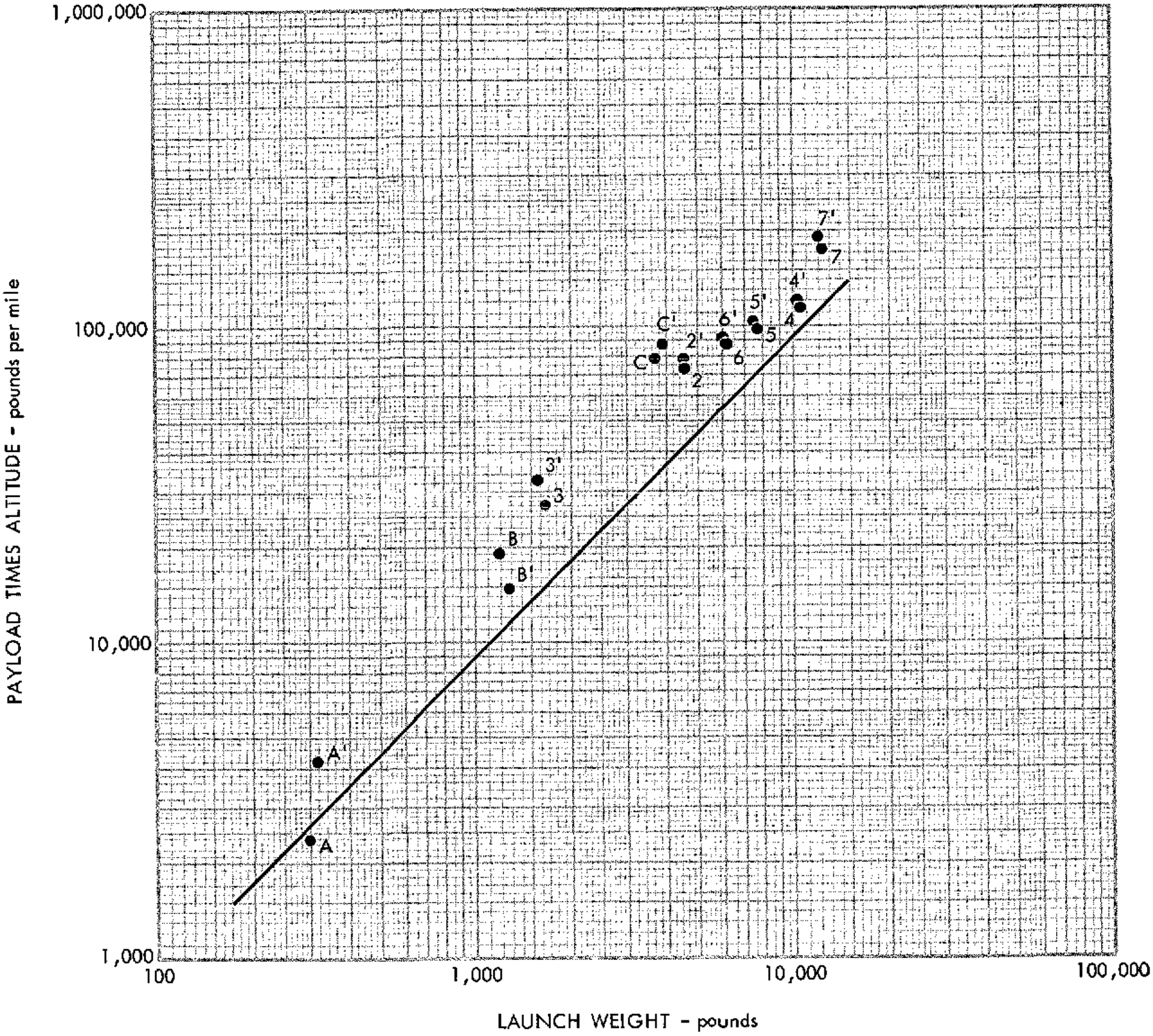
Vehicle Type	Vehicle Designation	Launch Weight	Payload	Altitude	Payload X Altitude
Hybrid	A	296	32	75	2,400
	B	1,189	88	210	18,480
	C	3,726	250	320	80,000
	A′	320	42	100	4,200
	B′	1,260	75	200	15,000
	C′	3,923	240	370	88,800
Solid	2	4,589	250	300	75,000
	3	1,631	250	110	27,500
	4	10,615	250	465	116,250
	5	7,657	250	400	100,000
	6	6,220	250	352	88,000
	7	12,246	250	715	178,750
	2′	4,520	250	318	79,500
	3′	1,506	250	125	31,250
	4′	10,546	250	479	119,750
	5′	7,532	250	421	105,250
	6′	6,026	250	368	92,000
	7′	12,052	250	768	192,000

Source: Stanford Research Institute.

The data in Table 22 are plotted in Figure 19 and overlayed on the trend line developed for existing vehicles in Figure 14. As shown, several of the new vehicles exhibit performance characteristics substantially greater than those of vehicles in current use. For example, hybrid vehicle A has a performance increase of 14,000 pound-miles over an "average" current vehicle having the same propellant weight. This amounts to a percentage increase of 50%, for this particular vehicle. Some of the other increases are even more substantial, as shown in Table 23.

FIGURE 19

PAYLOAD TIMES ALTITUDE AS A FUNCTION OF LAUNCH WEIGHT FOR NEW HYBRID AND ADVANCED SOLID DESIGNS *



* Vehicles are listed in Table 22.

SOURCE: Stanford Research Institute.

Table 23

PERFORMANCE INCREASE OF SELECTED NEW VEHICLES

Vehicle	Performance: New Vehicle (lb-mi)	Avg Current Vehicle of Same Weight (lb-mi)	Increase (lb-mi)	Percent Increase
B	19,000	11,000	8,000	73%
C′	89,000	36,000	53,000	147
2′	80,000	41,000	39,000	95
3′	31,000	14,000	17,000	121
4′	120,000	96,000	24,000	25
5′	105,000	70,000	35,000	50
6′	92,000	55,000	37,000	67
7′	192,000	110,000	82,000	75

Source: Stanford Research Institute.

These results do not prove conclusively that hybrid and advanced solid propulsion are applicable to sounding rockets. They do show, however, that a potential exists for considerable improvement over current vehicles, if performance values indicated for the new vehicles are achievable.

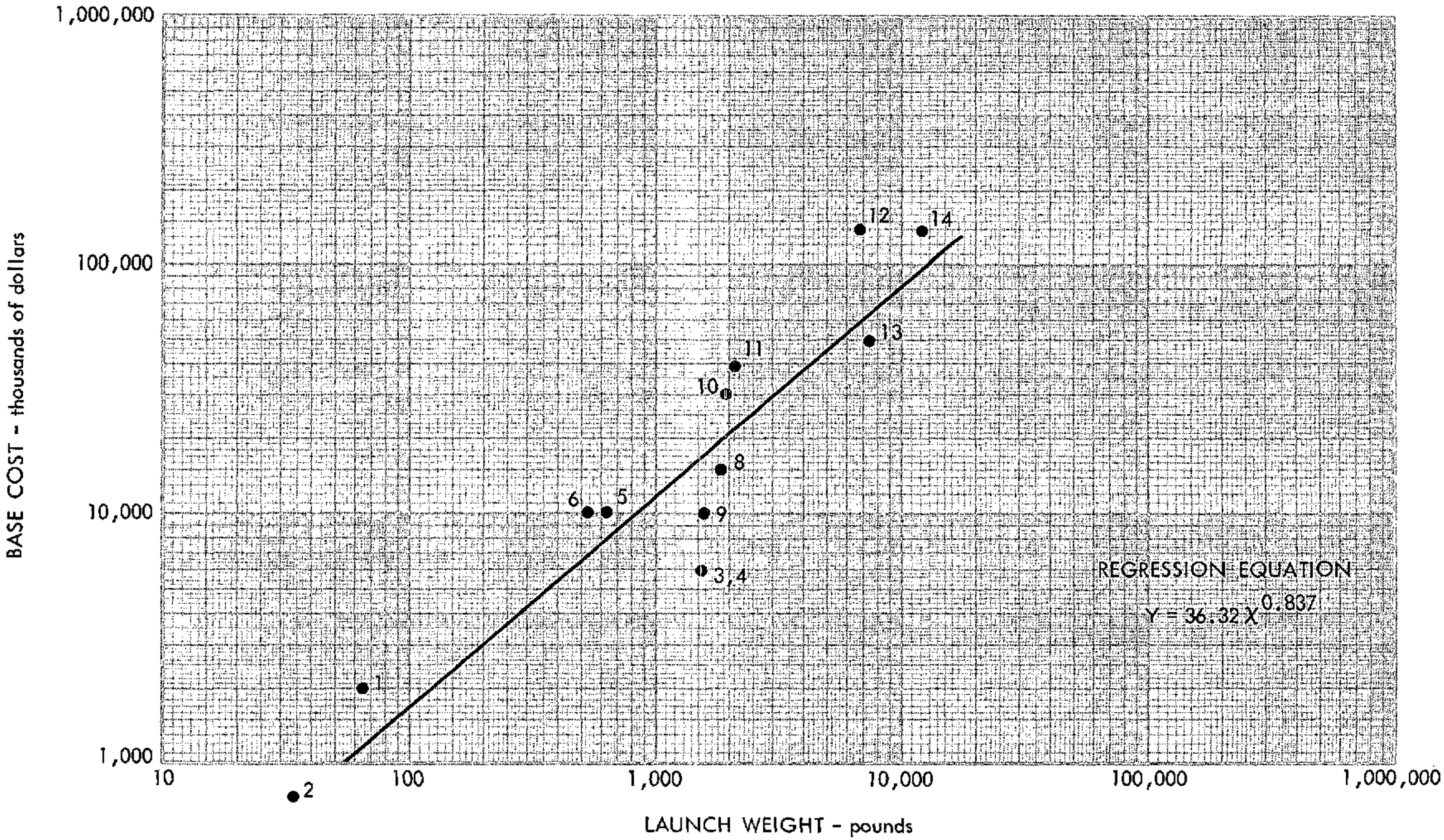
Cost and Cost-Effectiveness of New Hybrid and Advanced Solid Vehicles

A rough base cost for 14 current sounding rocket vehicles was given in Table 17. These vehicles represent a wide range of payload-altitude capabilities from the meteorological sounding rockets, Arcas and Judi-Dart, to the Journeyman and Scout vehicles used for very high altitude and orbital operations. The costs of these vehicles, with the exclusion of Scout, varied from $700 per unit for the Judi-Dart to $140,000 per unit for the Aerobee 350 and the Journeyman.

These costs, as well as the performance of the vehicles, exhibit a predictable relationship to launch weight. As shown in Figure 20, a strong correlation exists between cost and weight, when the variables are again plotted on log-log paper. Computation of a regression equation for the data points indicates that their distribution is even less than

FIGURE 20

BASE COST OF CURRENT SOUNDING ROCKETS AS A FUNCTION OF LAUNCH WEIGHT *



* Vehicles are listed in Table 18.

SOURCE: Stanford Research Institute.

that for the points shown in Figure 14, the plot of launch weight versus performance.*

If this equation is now used to predict base hardware costs for the new hybrid and advanced solid vehicles--using weight as the independent variable--a measure of cost-effectiveness may be determined for new vehicles with which to compare the cost-effectiveness of current vehicles. This is done in Table 24. Here, cost-effectiveness varies from $1.66 per

Table 24

COST AND COST-EFFECTIVENESS OF NEW HYBRID AND ADVANCED SOLID VEHICLES

Vehicle Type	Vehicle Designation	Launch Weight (lb)	Payload X Altitudes (lb-mi)	Cost Estimate ($)	Operational Cost-Effectiveness ($/lb-mi)
Hybrid	A	296	2,400	$ 4,000	$1.66
	B	1,189	18,480	13,000	0.70
	C	3,726	80,000	35,000	0.44
	A′	320	4,200	4,200	1.00
	B′	1,260	15,000	14,000	0.93
	C′	3,923	88,800	36,000	0.40
Solid	2	4,589	75,000	41,000	0.55
	3	1,631	27,500	17,000	0.62
	4	10,615	116,250	82,000	0.71
	5	7,657	100,000	64,000	0.64
	6	6,220	88,000	53,000	0.60
	7	12,246	178,750	95,000	0.53
	2′	4,520	79,500	41,000	0.52
	3′	1,506	31,250	16,000	0.51
	4′	10,546	119,750	82,000	0.68
	5′	7,532	105,250	62,000	0.59
	6′	6,026	92,000	52,000	0.57
	7′	12,052	192,000	92,000	0.48

Source: Stanford Research Institute.

* A linear regression curve fitting program was used to determine the regression equations in Figures 14 and 20. Correlation coefficients for the two equations are 0.912 for Figure 14 and 0.926 for Figure 20.

pound-mile for the smallest new hybrid to 40¢ per pound-mile for the largest hybrid. For the solid motors, cost-effectiveness is shown to be between 64¢ and 48¢ per pound-mile. These figures are clearly rough order of magnitude figures. Thus, no strong conclusions may be drawn as to their specific significance. The indication is again apparent, however, that the possibility exists for improving not only the performance of sounding rockets but the cost-effectiveness as well, using the new types of propulsion. Further research is required to establish more conclusive vehicle designs, which may be analyzed in greater detail.

APPENDIX

Table A-1

RDT&E COST BY STAGE
(Millions of Dollars)

Cost Element	Hybrid 2nd Stage	Hybrid Kick Stage	Solid Kick Stage	Solid Injection Stage	RSVP Kick Stage
Propulsion design and development					
Thrust chamber or solid motor	$ 6.8	$ 4.9	$ 7.5	$ 4.3	$ 6.3
Technology improvement	2.0	1.5	0.5	0.5	0.5
Development	2.1	1.4	3.0	1.6	2.6
PFRT	1.5	1.1	2.2	1.2	1.8
Qualification	1.2	0.9	1.8	1.0	1.4
Support structure, oxidizer assembly and pressurization system	$15.7	$10.7	$ 3.6	$ 3.6	$ 8.1
Design and development engineering	10.0	7.0	2.9	2.9	5.3
Subsystem test hardware*	2.5	1.9	0.5	0.5	1.4
PFRT hardware*	3.2	1.8	0.2	0.2	1.4
Stage development	$12.4	$ 8.7	$ 3.6	$ 3.5	$ 6.7
Systems integration	$ 7.5	$ 5.3	$ 2.2	$ 2.1	$ 4.0
Stage test engineering	4.9	3.4	1.4	1.4	2.7
Tooling and STE	0.8	0.6	0.4	0.4	0.5
Stage GSE	0.3	0.2	0.2	0.2	0.2
Flight test operations					
Engineering support	$ 3.0	$ 2.3	$ 0.8	$ 0.8	$ 2.0
Flight test hardware	$ 8.7	$ 7.0	$ 6.4	$ 5.1	$ 6.8
Stage structure and oxidizer system*	5.8	4.4	2.7	2.3	3.8
Thrust chamber assembly	1.1	0.5	1.6	0.7	0.9
Guidance and control system	1.8	2.1	2.1	2.1	2.1
Program planning and management	$ 3.4	$ 2.4	$ 1.0	$ 1.0	$ 2.0
Total RDT&E, excluding launch vehicle procurement	$51.1	$36.8	$23.5	$18.9	$32.6

* Includes 10% allowance for spares.

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Table A-2

SLV3X, AGENA, AND CENTAUR AVERAGE PER UNIT PROCUREMENT AND LAUNCH COSTS
(Dollars in Millions)

Cost Element	SLV3X			Agena Ascent Stage			Agena Orbital Stage			Centaur		
Number of launches	1-20	60	120	1-20	60	120	1-20	60	120	1-20	60	120
Component costs												
Basic hardware	$3.60	$2.88	$2.05	$0.80	$0.64	$0.46	$0.80	$0.64	$0.46	$8.4	$6.7	$4.8
Mission peculiar options	--	--	--	0.36	0.29	0.21	0.54	0.43	0.31	--	--	--
Spares	0.18	0.14	0.10	0.06	0.05	0.03	0.07	0.06	0.04	--	--	--
Launch operations	0.60	0.60	0.60	0.58	0.58	0.58	0.71	0.71	0.71	1.5	1.5	1.5
Vehicle systems tests	0.14	0.14	0.14	0.11	0.11	0.11	0.18	0.18	0.18	--	--	--
Logistics	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	--	--	--
Total cost per launch	$5.02	$4.26	$3.39	$2.41	$2.17	$1.89	$2.80	$2.52	$2.20	$9.9	$8.2	$6.3
Guidance and control (launch vehicle LV-3 On17)							0.36	0.36	0.36			
							$3.16	$2.88	$2.56			

Table A-3

PROCUREMENT AND LAUNCH COST FOR NEW STAGES
(Thousands of Dollars)

Cost Element	Hybrid 2nd Stage	Hybrid Kick Stage	Solid Kick Stage	Solid Inj. Stage	RSVP Kick Stage
Stage component costs					
Thrust chamber or solid motor	$ 220	$ 106	$ 325	$ 131	$ 185
Oxidizer system	131	68	--	--	49
Pressurization system	100	72	--	--	120
Attitude control	45	17	--	--	23
Batteries and wiring	135	95	--	--	--
Support structure	76	20	27	27	22
Total stage cost	$ 707	$ 378	$ 352	$ 158	$ 399
Shroud cost	222	272	215	215	240
Vehicle systems integration and assembly	340	250	230	180	240
Total first unit hardware cost	$1,269	$ 900	$ 797	$ 553	$ 879
Guidance and control astrionics	360	420	420	420	420
Launch operations	600	450	150	150	450
Total first unit cost per launch	$2,229	$1,770	$1,367	$1,123	$1,749
Cumulative average cost for 60 launches					
Stage hardware	1,015	720	638	442	703
Guidance and control	360	420	420	420	420
Launch operations	600	450	150	150	450
Total	$1,975	$1,590	$1,208	$1,012	$1,573
Cumulative average cost for 120 launches					
Stage hardware	723	513	454	315	501
Guidance and control	360	420	420	420	420
Launch operations	600	450	150	150	450
Total	$1,683	$1,383	$1,024	$ 885	$1,371

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